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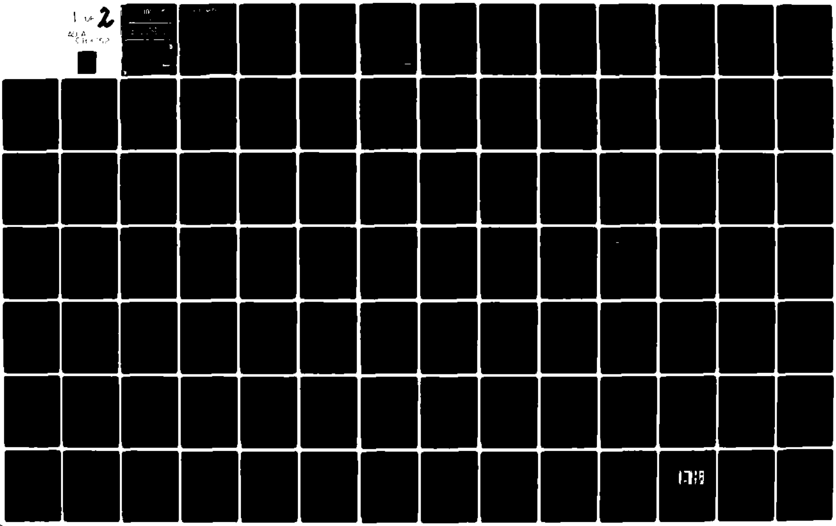

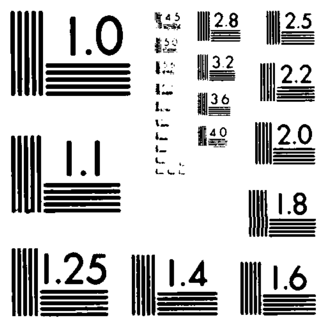

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Aircraft Turbine Engine Monitoring Experience: An Overview and Lessons Learned from Selected Case Studies

J. L. Birkler, J. R. Nelson

A Project AIR FORCE report
prepared for the
United States Air Force

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Two approaches have evolved in attempts to improve engine operations, maintenance, and management while reducing support costs. The first concentrates on short-term practices (inflight data are recorded in a snapshot mode). The second approach focuses on long-term benefits through improved knowledge of the operating environment. (Data must be recorded continuously on at least a few aircraft.) Engine duty-cycle research by the military services has demonstrated that neither the services nor the manufacturers have a clear idea of power requirements and frequent throttle movements during operational sorties in fighter aircraft and have generally overestimated engine parts life and underexpected life-cycle costs. The narrow concept of cost savings over the short term should not be the sole criterion on which monitoring systems are judged. Monitoring systems for recent and future engines should include continuously recorded data now that reliability, durability, and cost issues are almost on an equal footing with performance.

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PREFACE

In late 1977, the Deputy Chief of Staff/Research, Development, and Acquisition, Hq USAF, requested The Rand Corporation to investigate aircraft turbine engine monitoring experience. Conducted under the Project AIR FORCE project, "Methods and Applications of Life-Cycle Analysis for Air Force Systems," this research examined the utility of monitoring systems as a tool to improve short-term practices and long-term policies for aircraft turbine engines.

The research was undertaken to enrich understanding of the costs and benefits of monitoring systems, with the intent of then applying this knowledge to the F100 Engine Diagnostic System (EDS) program.[1]

This report discusses, and where possible analyzes, previous monitoring system experiences, which are directly applicable to current and future engine monitoring programs. Some long-term benefits that might be obtained from engine monitoring programs, but not considered in previous analyses, are also examined.

Hq USAF, the Air Force Systems Command, the Air Force Logistics Command, the Tactical Air Command, and the Deputy for Propulsion (Aeronautical Systems Division, AFSC), as well as Army and Navy programs, should be interested in the results. The techniques developed should also prove useful to a wide audience of analysts and decision-makers concerned with aircraft turbine engine monitoring or with the broader topic of life-cycle analysis.

[1] John Birkler and J. R. Nelson, Aircraft Turbine Engine Monitoring Experience: Implications for the F100 Engine Diagnostic System Program, The Rand Corporation, R-2391-AF, April 1979.

SUMMARY

An examination of the experiences gained from several aircraft turbine engine monitoring systems used over the last decade and a half[1] reveals that two approaches to engine monitoring have evolved in attempts to improve engine operations, maintenance, and management while reducing support costs. The first approach concentrates on short-term day-to-day operations, maintenance, and management practices. Usually, inflight data are recorded in a snapshot mode--a few seconds of data either at predefined performance windows or when certain engine operating limits are exceeded. The second approach focuses on long-term design-oriented benefits achieved through improved knowledge of the engine operating environment. To obtain the design-oriented benefits, data must be recorded continuously on at least a few aircraft.

U.S. monitoring systems have emphasized short-term, maintenance-oriented benefits, whereas the British have developed a system that has initially stressed long-term, design-oriented benefits. From a life-cycle analysis viewpoint, both types of benefits are worthy of consideration in any new monitoring system.

We have also reviewed engine duty-cycle research being conducted by the military services. This research has demonstrated that neither the services nor the engine manufacturers have had a clear idea of engine operational usage--of power requirements and frequent throttle movements occurring during operational sorties--in fighter aircraft. As a result, they have generally overestimated engine parts life and underestimated expected life-cycle costs. Although this situation has improved during the past several years, further improvement is needed.

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[1] To reflect the most recent monitoring system developments or programs would be a never-ending effort. Therefore, the research documented here reflects experiences before mid 1978.

There is much uncertainty about the benefits and costs that are attributable to engine monitoring systems. However, the narrow concept of cost savings over the short term should not be the sole criterion on which engine monitoring systems are judged. The benefits of anticipating maintenance, improving maintenance crews' understanding of problems as they arise, verifying that maintenance is properly performed, establishing relevant engine test cycles, and affecting future engine design--all of which we are as yet unable to quantify--can have substantial value. Indeed, the success of the on-condition maintenance concept will hinge on realization of these benefits, but they will take time to develop fully. Also, the modular design of recent engines requires some type of sophisticated fault isolation as the engine matures if on-condition maintenance is to be applied at the engine component level.

The Air Force should develop turbine engine monitoring systems for engines recently introduced into service and for future engines. Any new engine monitoring system should include the valuable contribution that continuously recorded data can make to the engine designer over the long term. Such information should help the services in maturing existing engines during component improvement programs (CIP), as well as in future engine design programs, especially now that reliability, durability, and cost issues are almost on an equal footing with performance.

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GLOSSARY[1]

Accelerated Mission Test (AMT):
An Air Force simulated operational mission ground test that compresses engine power cycles into a shorter test time.

Aircraft Integrated Data Systems (AIDS):
The broad term to identify a family of systems that acquires, processes and records data that are used to determine the functional status and condition of various aircraft systems, including the engine and engine components, on some commercial aircraft.

Baseline:
A physical condition or level of performance from which changes are measured.

Continuous Recording:
Data are recorded continuously during the entire flight or over a significant portion of the flight.

Damage Factor:
A relative number assigned to indicate a defined amount or unit of engine component or piece part life use: e.g., LCF counts, Hot Section Factor.

Engine Condition Monitoring System:
The complete approach to defining engine, engine component, and subsystem health status through the use of sensor inputs, data collection, data processing, data analysis (either manually or by machine), and the human decision process. This system can consist of either one integrated set of hardware or a group of engine monitoring devices.

Engine Diagnostic System (EDS):
The name currently used to describe the F100 engine monitoring system. This system is an Engine Condition Monitoring System.

Engine Health Monitoring System (EHMS):
Developed by the Air Force for the T-38 and F-5 aircraft.

Engine Trim:
Adjustment of the engine fuel control is called engine trimming. Engines are trimmed to compensate, within limits, for thrust deterioration caused by foreign deposits, material erosion, and other things that affect air flow through the engine as the engine

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[1] Where possible, we have tried to use definitions compatible with those of Society of Automotive Engineers, Inc., Committee E-32, Engine Condition Monitoring Committee.

accumulates operating time. Engines are usually trimmed after repair or replacement of any gas path components or controls to ensure that proper temperature, rotor speeds, and stall margins are maintained.

Engine Usage Monitoring System (EUMS):
A British system being applied to a wide variety of fixed-wing, rotary-wing, and VSTOL aircraft.

Failure:
A functional status or physical condition characterized by the inability of an engine, engine component, or subassembly to fulfill its design purpose. A failure will be the worst end condition of one or more malfunctions.

Failure Detection:
The process or technique of identification of engine, engine component, or subsystem failure.

Failure Mode:
The manner and sequence of events that indicate a specific engine, engine component, or subsystem failure.

Fatigue:
The formation and growth of cracks under repeated application of stress or strain.

Fixed Time Maintenance:
Maintenance actions are performed at certain times regardless of how well the engine is operating.

Ground Processing Station (GPS):
A ground station consisting of hardware and software at which the airborne data are reduced and stored.

Incipient Failure:
A functional status or condition before actual failure of engine engine component, or subsystem.

In-flight Engine Condition Monitoring System (IECMS):
Developed by the Navy for the A-7E aircraft.

Low Cycle Fatigue (LCF):
Refers to fatigue causing failure in less than 10,000 cycles

Limit Exceedances:
Parameter excursions beyond pre-established values.

Malfunction:
Abnormal condition or status of the engine, component, or subsystem.

Malfunction Detection Analysis and Recording System (MADARS):
Installed on all C-5A aircraft and is similar to the commercial AIDS systems.

Model Qualification Test:
The final military qualification, normally 150 hours on one engine, after which the engine is considered to be sufficiently developed for installation in a production aircraft.

Modular Engine:
The engine can be readily separated into subassemblies.

On-Condition Maintenance:
Maintenance based on the functional, structural, or other condition of the unit or part as differentiated from fixed-time maintenance.

Parameter:
A measurable or calculated quantity that varies over a set of values.

Primary Failure:
A failure that is not a result of another failure.

Secondary Damage:
Additional damage resulting from a primary failure.

Sensor:
A mechanical, electrical, optical, or fluidic device that provides data inputs--transducers, position indicators.

Signature:
A signal or combination of data inputs that are characteristic of an individual engine, engine component, or subsystem and can be used to indicate functional status and condition.

Simulated Mission Endurance Test (SMET):
A ground test based on continuous inflight recordings of a few engine and aircraft parameters for aircraft flown to current squadron mission profiles.

Snapshot Recording:
A few seconds of data either at predefined performance windows or when certain engine operating limits are exceeded.

Time Between Overhaul (TBO):
A maximum operating time for a particular engine, at the end of which time the engine must be returned to the depot for overhaul.

Time Temperature Recording System (TTR):
An engine monitoring concept that relies on measuring the time-temperature exposure of the engine hot-section and use of these data

as a measure of useful life consumed and material condition of the turbine.

Trend Analysis:
Using the change with time of measured parameters to diagnose or predict malfunctions.

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I. INTRODUCTION

Modern military aircraft turbine engines present new and increasingly difficult management, operations, and maintenance problems as their levels of operating performance, complexity, and cost continue to escalate. Even as propulsion technology advances, performance demands are at the edge of the available state of the art. New fighters and transports depend on engines that push the state of the art. During the 1970s, USAF has become increasingly concerned about the frequency and magnitude of engine problems encountered in new aircraft. Such problems often degrade the fighting capability of these aircraft and have on occasion resulted in the grounding of entire fleets.

An often proposed solution is electronic monitoring and recording of in-flight engine data. Several systems are currently in use. This report reviews selected case studies in the long history of turbine engine monitoring to highlight lessons learned that would be applicable to a new engine monitoring system under consideration today. Table 1 presents the six examples selected, their applications, and the time period they covered.[1] In addition, recent engine duty cycle research will be discussed.

Problems with previous engine programs and realization of the technical advance and increasing cost of high performance engines caused the Tactical Air Command in 1975 to issue a Required Operational Capability (ROC) for a new Engine Diagnostic System (EDS). The ROC stated: "New propulsion maintenance tools and managment practices must be developed to increase operational ready rates and system reliability, thus realizing full weapon capability of our fighter and transport aircraft."[2] Among the objectives was the elimination of engine disassembly for scheduled and periodic

[1] Section III contains a discussion of the case studies detailed in Refs. 1-17.

[2] Reference 18 provides insight into potential maintenance benefits as perceived by the Tactical Air Command.

Table 1

AIRCRAFT TURBINE ENGINE MONITORING SYSTEMS STUDIED

System	Application (Engine/Aircraft)	Time Period
Time-Temperature Recorder (TTR)	J57/F100D	1967-1969
Engine Health Monitoring System (EHMS)	J85/T-38A	1973-1977
Malfunction Detection Analysis Recording System (MADARS)	TF39/C-5A	1969-Present
In-flight Engine Condition Monitoring System (IECMS)	TF41/A-7E	1973-Present
Airborne Integrated Data System (AIDS)	Commercial	1969-Present
Engine Usage Monitoring System (EUMS)	British Aircraft	Early 1970s-Present

inspection, with engine maintenance for cause only, (a move toward on-condition maintenance). Central to the EDS concept is a growing awareness that traditional maintenance practices and capability may not be able to gauge the material condition or performance level of current or future engines with the desired precision, which leads to conservative maintenance policies and may result in needless disruption of system continuity or ignorance of developing problems. Issuance of the ROC identified the EDS as a tool some in the Air Force believe is necessary to redirect current engine maintenance and management practices. In particular, it is expected to play a central role in on-condition maintenance, a concept significantly different from past practices.

This study reviews the selected engine monitoring systems to obtain experiences that might apply to new monitoring programs and develops an analytical method that aids in understanding their outcomes. The analytical method may aid high level decisionmakers in their decisions concerning acquisition of new monitoring systems.

II. WHY ENGINE MONITORING?

Organizations responsible for engine operations, maintenance, and management, as well as the design and test communities, have for years proposed monitoring and recording engine parameters during flight operations. Each believed these data would aid in the decisionmaking process by removing some of the uncertainty in their disciplines. If adequate data regarding engine material condition, performance levels, and operational duty cycles could be obtained by current conventional reporting and data collection procedures, there would be no need to add a sophisticated engine monitoring system to an already complex piece of turbomachinery. The inability of some in-flight crews to supply necessary engine data does not stem from a lack of interest, because their survival depends upon a properly functioning power plant. However, fighter pilots, for example, have heavy workloads in complex cockpits and must perform many other functions. The pilot's senses may detect a malfunction and turn his attention to the cockpit gauges to confirm it. However, he may not sense some events such as overtemperature.

The pilot's report is the basis for maintenance attempts to duplicate the problem on the ground by testing the engine either on the aircraft or after it has been removed. It takes many years of experience and a continuing training program to produce a skilled jet engine mechanic; still, in many respects, modern military jet engine maintenance is an art. The mechanic relies on previous experience in diagnosing the malfunction. If the engine is a new or maturing power plant, rather than one that has been in service for some time, the procedure can be hit or miss.

After a pilot reports a malfunction, the maintenance crew analyzes the pilot's report, the engine's history, and available ground data and may test the engine in attempting to understand and possibly to duplicate the reported problem. If the malfunction cannot be duplicated, maintenance may remove and replace an engine or

an engine accessory, such as a fuel control, or forward that engine or accessory to the next higher level of maintenance. They could even declare the engine operational and reinstall it on an aircraft if the engine appears to be in satisfactory condition. Whatever events follow the pilot's write-up, uncertainty can remain over whether there was a problem, how serious it was, and whether the correct action was taken. This approach may generate unnecessary repair actions and needlessly consume spare parts, fuel, time, and facilities. In some instances where the problem is not fixed or another problem is introduced because of the maintenance action, safety of flight could be compromised.[1]

The need to minimize the effect of operational failures is evidenced by the frequent grounding of military first line fighter and attack aircraft, followed by an interval of low engine availability during correction of the engine material or design deficiency. The problem of grounded aircraft principally affects military systems because of their advanced level of technology and the short time span during which aircraft and engines are acquired and introduced into operational service.

From the unsettling experience of the first few engine failures to confirmation of a design or material defect, which in turn leads to redesign, testing, production, and finally installation of a corrected part, the new part requires, at a minimum, 18 months of intensive effort by the military service and the engine contractor. During this time the weapon system operates at less than full potential, often requiring frequent inspections and replacement of the deficient part until the new part becomes available and is installed. The cost of correcting a major engine design or material deficiency is measured in the millions of dollars. If the problem is critical, the fiscal resources required to correct the problem might even be obtained by reallocating dollars from other weapon systems or support functions. Although the direct dollar cost can be substantial, it does not reflect the reduction in military capability or the inefficiencies associated with crisis management.

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[1] See Ref. 19 for a more complete discussion.

On-condition maintenance, a maintenance policy recently adopted by the Air Force for the F100 engine, was intended to overcome these supposed shortcomings of the traditional fixed-time maintenance for military engines. However, more information is needed than is currently available to military operators to fully carry out such a policy. Monitoring is expected to fulfill this need. Commercial experience has shown that the engine, with its various pressures, temperatures, and rotating speeds, projects a clear picture of detectable wear and signals incipient failures due to deterioration of various engine components.

The potential short-term and long-term benefits available from engine monitoring can significantly affect day-to-day squadron operations, maintenance policies, and near-term management as well as testing, design, and long-term management policy.

SHORT-TERM BENEFITS

Short-term benefits of aircraft turbine engine monitoring systems are those associated with improvements in daily operations, maintenance, and management at an operational base. Such improvements might be in safety, reliability, scheduling and planning of flight operations, maintenance activities, and logistic support.

The operator is primarily concerned with safety of flight and continued engine operation at performance levels specified so that payload, range, time on station, and fuel are adequate for the desired missions. The operator is also the first link in the maintenance chain. He initiates unscheduled maintenance based on his perceptions of engine health. (A particularly difficult category for him to deal with is engine overtemperature, which calls for specific maintenance actions depending on the overtemperature's magnitude and duration, both of which depend on pilot recall.) Uncertainty as to an engine's condition has resulted in the past in conservative maintenance policies and practices. Conservatism adversely affects engine reliability and overall aircraft system availability if it retards reliability improvement. The inability to isolate and verify a malfunctioning engine component results in time-consuming troubleshooting and fault isolation procedures.

Engine monitoring is expected to improve maintenance capability through better understanding of problems associated with the internal parts of the engine and to isolate malfunctioning components through analysis and trending of day-to-day data. Expected benefits of improved fault isolation include the reduction of maintenance man-hours required for troubleshooting, lessening of removal/replacement actions, fewer parts needed, and less bench checking of components. Also, less fuel and fewer test facilities may be required for ground testing.[2] The potential benefits of trending engine parameters lie in the ability to forecast individual engine removals by cause, thus not only predicting the removal but anticipating the spare parts, maintenance skills, equipment requirements, time necessary to repair the engine and return it to service, and after the maintenance action confirm the problem is corrected.

LONG-TERM BENEFITS

Long-term benefits of aircraft turbine engine monitoring systems are those improvements associated with engine design, testing, product improvement, and management policies in operations and maintenance, which take some years of experience to analyze.

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[2] Engine monitoring is expected to result in substantial fuel savings by maintaining engine performance, disclosing when certain performance parameters are out of bounds (thus minimizing operational fuel consumption), reducing the length of engine ground trims, and reducing the length and frequency of ground testing. Whether such fuel savings actually happen is another matter. Operating squadrons receive a fuel allotment, and the apportionment among engine trims, ground testing, and flight hours is a function of the operational reliability of the engine, and thus of the testing and number of trims required. If the decreased ground utilization materializes, one would assume either a net fuel saving or more fuel available for flying, and thus a proportional increase in flying time. Conversely, if monitoring identifies more minor problems, requiring an increasing frequency of trims and tests (for a maturing engine, for instance), flight hours might be adversely affected unless squadron fuel allocation is increased. If the benefits of monitoring are realized, the two outcomes that might be expected are either continued fuel usage at allotted levels, thus increasing flying hours with no reduced fuel costs, or reduced fuel costs at a fixed flying activity rate.

Military aircraft weapon systems are designed to specific mission profiles, based on requirements for generalized combat missions with specified weapons loads and avionics suites. Missions have emphasized payload, radius, and loiter and combat time. Other specific performance requirements for particular applications--such as hot-day takeoff capability, aircraft acceleration, excess specific power, extremes of 1 g envelope requirements, carrier wave-off, and altitude ceilings--are also evaluated. However, there are no detailed missions to assess how the aircraft will actually be used in combinations of combat and training. An improved understanding of the mission spectrum to be flown is necessary to establish the design requirements for the operational environment of the aircraft and its propulsion and related subsystems.

Understanding the operational environment is an important element in establishing design criteria, because future engines, designed to smaller margins, will tend to be <u>more</u> sensitive to deviations from expected loadings. Thus, as the available margins diminish, a more precise understanding of aircraft system uses, training as well as combat, will be a required input to competently design new engines. Although latent design deficiencies in new engines can never be totally avoided, problems resulting from engine design specifications and test procedures that are not compatible with design mission operations can be alleviated.

The predominant cost of an aircraft engine development program is incurred in building hardware and accumulating test experience. The primary means for achieving the required durability and reliability is through full-scale engine testing. The more testing, the more confidence that the desired durability and reliability are achieved.

Historically, the military has considered that a "normal" engine development requires 10,000 to 15,000 full-scale test hours and 20 to 30 nameplate engines before the Military Qualification Test (MQT) be undertaken.[3] Successful completion of the MQT, a 150-hour

[3] During this period one can expect about 40 major failures, 4000 design changes, and 2500 engineering changes. Reference 20 contains an excellent discussion of aircraft propulsion development.

endurance test, releases the engine for production.[4] In spite of the 10,000 or more test hours, the durability and reliability records of new engines, or even uprated versions of earlier engines, are generally poor during the first few years of service. New testing procedures are expected to improve this situation. The Air Force Accelerated Mission Test (AMT) and the Navy Simulated Mission Endurance Test (SMET) are steps in this direction. (Both are discussed in Sec. V.)

Engine problems are often rationalized, citing material or design deficiencies, by implying that the engine is highly advanced in technology. This is certainly true in some cases, but current research reveals that the operational environment and the severity of the engine's duty cycle are not fully appreciated, also resulting in substantial problems not expected or accounted for during design. In the past, design mission profile specifications bore only a superficial resemblance to operational missions.[5] In short, engineering awareness of the operational environment has been inadequate, contributing to low initial reliability, which must be corrected during extensive post-MQT engineering during the Component Improvement Program.[6]

The testing cycles used during engine development and MQT qualification usually grossly underestimate the frequent power cycling that occurs during operation.[7] An expected long-term monitoring benefit is that the engine's duty cycle will be highly visible. If the duty cycle should significantly alter because of a change in policy, mission profile, or threat, test cycles could also be updated. Engine monitoring can help ensure that the original design criteria and qualification test requirements for aircraft propulsion systems are structured to meet intended use. Correlating test results with expected operational usage is important when the

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[4] Statistically, a 150-hour test on a sample of one or two engines reveals little, if anything, about the operational endurance of the engine.

[5] Reference 6 quantifies some of these differences.

[6] References 7, 8, 21, and 22 discuss this.

[7] See Refs. 23, 24, and 25.

services project how well a new engine design will hold up. The data base can also help to evaluate redesign of existing components in engines currently qualified.[8] When the operational cycles are coupled or integrated with other tests required during qualification, there would be higher confidence that design or material changes will achieve, not exacerbate, the intended performance and durability goals.

In addition to the design and testing benefits, verification of new operations and maintenance policies should aid management in considering initiation of new, longer-term policies with regard to life management or the correct structuring of maintenance organizations (i.e., repair levels for different applications of engines). Long-term logistics support at depots and bases could be considered in a total system context rather than a piecemeal fashion if improved operational and maintenance data are available.

AN ENGINE MONITORING BENEFITS MATRIX

To shed light on the strengths and weaknesses of previous monitoring systems, we have devised an evaluation matrix to be used in analyzing past experience. Although the matrix will not be discussed until Sec. IV, we need to introduce the row headings of the evaluation matrix before we discuss the case studies. (The selected case studies serve as column headings.) We do this to alert the reader to characteristics that were found to be desirable in an engine monitoring system. Table 2 lists these characteristics, which are drawn from several sources. Most are design objectives for the selected case studies, others emerged from operational experience--not having been anticipated during the concept formulation phase of the original system. All are desirable in an engine monitoring system.

To facilitate thinking about these characteristics, we use a time orientation to organize them into two main groups: maintenance oriented (short-term benefits) and design oriented (long-term

[8] If aircraft use is changed, the operational duty cycle for the engine must be redefined, because a change in usage will cause different failure modes in the engine.

benefits). The former group is further divided along functional lines: operational, maintenance, and management. After reviewing the selected case studies, we use the matrix format to provide insights as to how well engine monitoring systems have achieved certain of their design objectives in the past, but more important, what objectives might be sensible for new engine monitoring systems in the future.

Table 2

ENGINE MONITORING SYSTEMS EXPECTATIONS

Maintenance Oriented

- o Operational
  - -- Aware of engine health
  - -- Aware of engine overtemperatures
- o Maintenance
  - -- Less maintenance manpower
  - -- Less troubleshooting and trim fuel
  - -- Fewer engine removals
  - -- Less parts consumption
  - -- Anticipate maintenance (trending)
  - -- Improve cause and effect understanding
  - -- Validate maintenance action
- o Management
  - -- Modify TBO
  - -- Provide configuration control

Design Oriented

- o Guide CIP
- o Correlate test/duty cycles
- o Aid future engine design
- o Assist management in new policy formulation

III. SELECTED CASE STUDIES

The selected case studies in Table 1 reflect Air Force, Navy, commercial, and British applications of engine monitoring systems. The monitoring systems were applied to engines for U.S. military fighter, attack, trainer, cargo, and commercial transport aircraft, and to a spectrum of British aircraft. Applications include both single pilot and multicrew aircraft and single and multi-engine designs.

The monitoring systems themselves ran the gamut of parameter measurement. The TTR system measures only a single engine parameter whereas IECMS currently measures in excess of 50 parameters. Most of the systems used snapshot recording; others recorded data continuously. The operational focus of the monitoring systems was also varied. The U.S. systems are oriented primarily toward improving day-to-day maintenance, whereas the British system has initially ignored the short-term maintenance benefits, choosing first to emphasize the longer-term feedback of operational data to the design and test communities. An identified control group existed for several of the monitoring systems. Unfortunately, the control groups did not control for all variables of interest, and the time for most tests was too short to stabilize inputs and quantify some of the possible outcomes. Nevertheless, although all the information desired is not available, much useful information was obtained.

This section synthesizes the experience from the case studies.

TIME TEMPERATURE RECORDING (TTR) SYSTEM

Background

The Time Temperature Recording (TTR) system, sometimes referred to as Hot Section Analyzer System (HSAS), was originally proposed in the mid 1960s as a possible means of scheduling engine depot maintenance depending on engine condition rather than at fixed time intervals. The service test evaluated the TTR technique for predicting

engine condition on a flight-to-flight basis and whether TTR would reduce flight line maintenance. The concept was to measure an engine's time-temperature exposure and use the data as an indication of engine hot-section life consumed. The approach used a Hot Section Factor Count (HSFC) based on metal creep rate. A variable-rate counter that followed the creep curve and integrated the area under the curve yielded a HSFC that it was felt would provide a measure of the material condition of the turbine. The creep curve used was for the first-stage nozzle (one of the most critical hot-section parts) of the J57-P-21 engine used in the F100 fighter aircraft.

The TTR approach proved no better than operating time for assessing hot-section material condition. This conclusion reflected pragmatic operational effects, such as:

- The engine's hot section is composed of a variety of materials;
- Material homogeneity is lacking for hot-section parts;
- Hot-section parts vary in age and accumulated creep;
- Other failure modes (low cycle fatigue, thermal shock, etc.) were excluded from the HSFC.

Partially because of the limited success of total HSFC as a predictor of time between overhauls and the trend toward using time-temperature recording systems as a daily maintenance tool, Sacramento Air Material Area contracted with ARINC Research Corporation to evaluate the time-temperature recording method as a tool for predicting engine problems on a day-to-day basis on the F-100 aircraft. The test program began in September 1967 and ended during November 1968 using F-100 aircraft of the 355th Tactical Fighter Squadron located at Myrtle Beach AFB. The approach was to have both instrumented and uninstrumented aircraft from the same squadron. By January 1968 five F-100 aircraft were modified. On 1 February, the 355th Tactical Fighter Squadron deployed to Phu Cat Air Base, Republic of Viet Nam, where two additional aircraft were

modified. The following case study focuses on the experiences and results reported by ARINC.[1]

Technical Approach and System Description

The service test evaluated the TTR techniques for predicting engine condition on a flight-to-flight basis and whether TTR would reduce flight line maintenance. The TTR system used the output from four dual thermocouples on the J57-P-21 engine to provide a continuous indication of the Exhaust Gas Temperature (EGT). In addition to the recorded data, EGT was displayed to the pilot both digitally and through a conventional gauge with an amber warning light when the average EGT exceeded 665°C. Two high-temperature clocks were activated--one when average EGT exceeded 640°C and the other when it exceeded 670°C. Two high-temperature flags were activated when average EGT exceeded 690°C and 760°C. Upon pilot activation, the indicator displayed the temperature difference between the maximum and minimum reading thermocouples; this display provided a means of detecting fuel-nozzle clogging and burner can burn-through.

Earlier use of TTR on F-102, F-105, and F-106 aircraft suggested that HSFC divided by flight time (i.e., Hot Section Factor Rate--HSFR) would define a useful parameter that would indicate engine health. An additional requirement was that there should be no sudden unexplained increase in HSFR. The following criteria were established for the F-100 aircraft:

- The HSFR shall not exceed 150 counts per hour on any flight, excluding functional check flights;
- The HSFR shall not increase by more than 50 counts per hour over the average HSFR for the last 10 hours of flight;
- The ground-stabilized EGT shall not exceed 630°C;
- The EGT spread shall not exceed 80°C.

[1] For a complete discussion see Ref. 5.

Because there was no past experience in the use of a TTR system on the F-100 aircraft, the above criteria were used as a first approximation with the understanding that more effective limits might be established at a later date. However, follow-on examination revealed that neither single nor multiple-limit alternate criteria proved effective in assessing engine condition.

Experience

This section summarizes the data collected and analysis conducted by ARINC. There were four basic divisions of field-data acquisition: instrumented and uninstrumented aircraft at Myrtle Beach Air Force Base and Phu Cat Air Base. Comparisons were made to discern differences among the four engine groups. The TTR outputs of the instrumented aircraft were related to the existence of engine problems on a flight-to-flight basis to evaluate the usefulness of time-temperature recordings as a daily maintenance tool. Table 3 summarizes activity.

Table 3

ACTIVITY SUMMARY FOR INSTRUMENTED AND UNINSTRUMENTED AIRCRAFT

Activity	Instrumented Aircraft	Uninstrumented Aircraft
Number of aircraft	7	23
Flight hours	2907	6650
Flights	1817	3736
Malfunction reports		
Pilot	146	261
Maintenance	123	138
Ground maintenance manhours	3356	5704
EGT-related maintenance manhours	1832	2736

SOURCE: Data derived from tables in ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

Analysis of Available Data

Only 26 maintenance actions were originated on the basis of TTR information--6 at Myrtle Beach and 20 at Phu Cat. Table 4 summarizes the TTR-initiated maintenance.

ARINC reports that the limits established--HSFR 150 and HSFC 50--were exceeded on 329 missions; however, these special limits did not apply in a combat environment.

Table 4

SUMMARY OF TTR-INITIATED MAINTENANCE

TR Function that Initiated Maintenance	Number of Complaints Initiated	Number of Actions Taken	Number of Verified Malfunctions	Maintenance Actions
HSFR	12	11	8	4 uptrims, 4 downtrims
Δ HSFR		2	0	
HSFR and 640°C Clock		2	0	
640°C Clock	3	2	0	1 precautionary hot-section inspection
HSFR and Δ HSFR	3	3	2	1 uptrim, 1 AB oversize
665°C EGT gauge light	2	2	0	
690°C flag	4	3	0	2 precautionary hot-section inspections
TTR system	1	1	0	
Total	29	26	10	

SOURCE: Data derived from tables in ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

Table 5 defines the terminology used in Table 6, which summarizes the aircraft maintenance actions and manhour data recorded by ARINC.

From the data of Table 6, it can be seen that use of the TTR equipment in Viet Nam increased EGT-related flight line

Table 5

ANALYSIS TERMINOLOGY

Terminology	Data Category
U_{US}	Uninstrumented-aircraft data acquired in the United States and its territories
U_{VN1}	Uninstrumented-aircraft data acquired in Viet Nam for the period 1 February 1968 to 30 April 1968
U_{VN2}	Uninstrumented-aircraft data acquired in Viet Nam for the period 1 May 1968 to 15 November 1980
I_{US}	Instrumented-aircraft data acquired within the United States and its territories
I_{USH}	Instrumented-aircraft data (United States) exclusive of Hot-Section Analyzer failures
I_{USHM}	Instrumented-aircraft data (United States) exclusive of Hot-Section Analyzer failures and exclusive of maintenance initiated as a result of Hot-Section Analyzer readings
I_{VN}	Instrumented-aircraft data acquired in the Republic of Viet Nam
I_{VMH}	Instrumented-aircraft data (Viet Nam) exclusive of Hot-Section Analyzer failures
I_{VNHM}	Instrumented-aircraft data (Viet Nam) exclusive of Hot-Section Analyzer failures and exclusive of maintenance initiated as a result of Hot-Section Analyzer readings

SOURCE: Data derived from tables in ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

Table 6

FLIGHT LINE MAINTENANCE ACTIONS AND MANHOURS

	U_{US}	I_{US}[a]	I_{USH}[a]	I_{USHM}[a]	U_{VN2}	I_{VN}	I_{VNH}	I_{VNHM}
Total flight hours	2226.0	436.2	436.2	436.2	2309.9	2471.0	2471.0	2471.0
Total unscheduled maintenance actions	141	40	31	25	150	201	164	144
Total maintenance manhours	2190.9	465.7	391.6	376.2	2401.6	2890.3	2688.2	2530.7
Manhours per flight hour	0.984	1.068	0.898	0.862	1.040	1.170	1.088	1.024
EGT-related maintenance manhours	1122.7	252.5	178.4	163.0	1132.0	1579.3	1377.2	1219.7
Manhours per flight hour	0.504	0.579	0.409	0.374	0.491	0.639	0.557	0.494

SOURCE: *Data derived from tables in* ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

[a]These maintenance manhour *ratios are of questionable value because five of the seven engines flew* less than 30 hours between installation and Viet Nam deployment.

maintenance 16 percent (0.639 vs. 0.557) because of TTR equipment maintenance and 13 percent (0.557 vs. 0.494) because of TTR data.[2]

ARINC reported, "It is not known how flight-line maintenance would have been affected if maintenance actions had been taken every time a special limit was exceeded; however, on the basis of the results of the 26 actions conducted, a significant increase in flight-line maintenance could be expected." (See Table 4.)

Table 7 summarizes the number of actions and manhours required to maintain the TTR equipment, and the actions and manhours expended as a result of the TTR data.

Table 7

SUMMARY OF TTR MAINTENANCE EVENTS

Maintenance Category	Experience: United States	Experience: Viet Nam
TTR-equipment maintenance		
Actions	9	37
Manhours	74.1	202.1
TTR-initiated maintenance		
Actions	6	20
Manhours	15.4	157.5

SOURCE: Data derived from tables in ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

Findings

Based on the criterion of HSFR $\geq$ 150, the TTR data correctly indicated engine problems 44 percent of the time when the engine had a problem (see Table 8) and generated unnecessary maintenance

[2] The limits--HSFR > 150 and HSFC > 50--were exceeded on 329 missions; however, these limits did not apply in a combat environment.

in 15 percent of the flight sorties flown. The second criterion proved only slightly better (see Table 9). The final conclusion *was that neither criterion was effective in detecting hot-section* problems.

Table 8

EVALUATION MATRIX: HSFR $\geq$ 150

		Analyzer indicates that engine is:	
		Good	Bad
Engine is actually:	Good	1308 flights	243 flights
	Bad	39 flights	31 flights

SOURCE: Data derived from tables in ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

Table 9

EVALUATION MATRIX: Δ 50 HSFR

		Δ HSFR indicates engine is:	
		Good	Bad
Engine is actually:	Good	1202 flights	150 flights
	Bad	45 flights	20 flights

SOURCE: Data derived from tables in ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

Overtemperature Reporting. Pilot-reported and TTR-recorded overtemperature magnitude and duration are compared in Table 10.

The EGT levels of 670°C and 690°C were chosen because: (1) pilots are required to report magnitude and duration of engine overtemperatures at these levels, (2) these temperatures were monitored by a TTR flag and overtemperature clock, and (3) F-100 Technical Order directs a hot-section inspection be performed if any engine accumulates over two minutes at 670°C, or momentarily exceeds 690°C.

Table 10

PILOT-REPORTED AND TTR-REPORTED OVERTEMPERATURE

Criteria	Pilot-Reported: Uninstrumented Aircraft	Pilot-Reported: Instrumented Aircraft	TTR Reported
Total flight hours	4545.9	2907.2	2907.2
Number of flights	2557	1830	1830
Seconds recorded above 670°C	129[a]	3	150
Occurrences reported above 670°C	12	8	42
Occurrences reported above 690°C	6	3	9
Occurrences reported above 760°C	0	0	0

SOURCE: Data derived from tables in ARINC Research Corporation, "Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft," Annapolis, Md., 1969.

[a]Includes one mission during which 120 seconds above 670°C was reported.

ARINC's conclusions from Table 10 were:

- o In reporting high EGT levels pilots using instrumented aircraft are not appreciably different from pilots using uninstrumented aircraft.
- o Pilots are more likely to report major overtemperature conditions (>690°C) than minor overtemperature conditions.
- o Pilots report 1/3 of the major overtemperatures, 1/5 of the minor overtemperatures, and a very small fraction of the total high-temperature durations.

Although trending was not an object of this program, ARINC did trend the available data and reported the following conclusions. First, several engine removals were immediately preceded by EGT and HSFC peak values; second, trending indicates changes induced by maintenance and shows whether these changes are desirable; and third, trending of ground EGT recordings is preferred, because these are not influenced by changes in mission profile.

In any analysis of turbomachinery, the time since last overhaul is an important consideration, because any difference in time since last overhaul or flight hours distributions can explain the results. ARINC did examine time since last overhaul and reported that the uninstrumented engines were approximately 85 hours older and remained in service approximately 30 percent longer between periodic inspections than the instrumented engines.

In addition to the normal hardware problems, ARINC encountered three people-related problems. The first was lost or doubtful data because of failure to record and reset the analyzer after flights. ARINC concluded that "the basic cause for many of these reporting problems was a lack of confidence in the analyzer system and the belief that its use could result in inspections or removals not required by existing limits or engine operation." The second problem was four flights flown with the EGT circuit inoperable. Pilots were unaware of EGT indicator failure or did not consider the loss of EGT indicators justification to abort the mission. The third problem

reflects the ability to recognize an obvious equipment malfunction. During the F-100 test program, an aircraft sustained a tire failure on landing. When the TTR equipment was checked, all EGT flags and clocks were activated but no HSFC had been recorded. This obvious equipment malfunction was unrecognized, and the engine was removed.

The data reveal that initially an increase in maintenance resulted. Whether this increase resulted from discovering more engine problems or reflected increased pilot and maintenance personnel sensitivity is not clearly discernible. Even though the test was not successful in finding a set of criteria that could be used effectively without introducing a large number of false maintenance actions, much was learned about the J57-P-21 engine and its operation. The unsuccessful test results precluded any effect on engine management or future engine design.

ENGINE HEALTH MONITORING SYSTEM (EHMS)

Background

The Engine Health Monitoring System (EHMS) dates back to early 1965, when the Air Training Command (ATC) wanted to extend the J85 engine periodic inspection interval. One approach ATC initiated was to investigate continuously monitoring installed engine performance versus traditional maintenance--remove, disassemble, and inspect. The original concept required ground operation at predetermined intervals, which resulted in scheduling and facility limitations. To overcome these limitations, in September 1971 Northrop Corporation submitted an unsolicited proposal to ATC outlining a three-phase effort to develop an airborne EHMS. Phase I was a prototype phase where EHMS-J85 integration was to be demonstrated. Phase II would entail the modification of a number of aircraft and engines to collect system data in an operational environment. Fleetwide implementation of EHMS was to take place in Phase III. Early in 1972 Hq USAF directed the Air Force Logistics Command (AFLC) and ATC to proceed with Phase I, which was completed in August 1973. Phase I hardware demonstration involved two aircraft and six engines. The

program achieved 900 hours of total engine operation. The cost of the program was shared between the USAF ($238,000) and Northrop ($378,000). Hq USAF approved initiation of Phase II in December 1973.

Phase II evaluation was to determine the effect of EHMS on seven operational and logistic categories: (1) engine performance and trending of installed engines; (2) engine maintenance and manpower reductions; (3) engine spare parts reductions; (4) reductions in engines overhauled for cause; (5) increased aircraft operationally ready rate; (6) reduction in fuel consumed for reduced maintenance actions; and (7) reduction in secondary damage from undetected engine component failures. The EHMS-instrumented aircraft were to be compared with ten unequipped aircraft operated from the same base under similar conditions. AFLC e67ected Phase II to provide a statistically significant data base from which decisions could be made regarding the benefits of the EHMS on the T-38 in the ATC environment.

The Phase II operational test was conducted by ATC at Randolph AFB, where ten T-38 aircraft and 22 engines were modified with the EHMS equipment. The EHMS-equipped aircraft were first operational at Randolph AFB in November 1975. Equipment problems held up the test start until July 1976. The objective of the service test was attainment of 3000 monitored engine flying hours, which was achieved in May 1977. In addition to the EHMS aircraft, maintenance records for a control group of unmonitored engines were kept for comparison.

System Description and Technical Approach

The T-38 EHMS emphasizes improved day-to-day engine maintenance. The EHMS consists of two units, an airframe-mounted Electronic Processing Unit (EPU) and a ground-based Diagnostic Display Unit (DDU).

Electronic Processing Unit. The on-board EPU monitors selected engine parameters (see Table 11) that are multiplexed, converted into a digital format, and recorded.

Table 11

INPUT PARAMETERS MONITORED BY EHMS

Existing	Quantity	Added	Quantity
N (rotor speed)	2	P_{AMB} (ambient pressure)	1
W_F (fuel flow)	2	P_{TO} (dynamic pressure)	1
A_8 (nozzel position)	2	P_{S3} (compressor discharge pressure)	2
Engine oil pressure	2	P_{S6} (turbine discharge pressure)	2
T_{5H} (EGT)	2	T_{TO} (total temperature)	1
Anti-ice switch	1	Engine oil temperature[a]	2
Landing gear position	1	Compressor vibration	2
F/C Hydraulic pressure	1	IBV/Bleed valve position	2
Utility hydraulic pressure	1	PLA (throttle angle)	2
A/C Signal reference	1	Fuel boost pump pressure	2
28 V DC Power	1	Anti-ice temperature[a]	2
28 V 400 Hz Reference	2	Pilot data switch	2
Total	18	Total	21

[a]Removed during test program.

Data were recorded only when parameters exceeded previously established limits, upon pilot command, or automatically when preselected flight conditions were satisfied: (a) before takeoff when both throttles are at military and the engine is stabilized for at least four seconds, (b) during takeoff when the weight comes off the landing gear, (c) during climb between 10,000 and 20,000 feet if both throttles are at military for at least 12 seconds, and (d) during cruise above 20,000 feet and both throttles at military for at least 12 seconds. If any of these conditions occur, the airborne unit records all parameters as of that moment (snapshot recording). The airborne system monitored both engines. Installed weight, including engine sensors, wiring harness, and EPU, was approximately 34 pounds and required approximately 200 manhours to install per aircraft.

Diagnostic Display Unit. The DDU is a portable data interpreter and display unit. After landing, the DDU retrieved flight data stored in the EPU, which could be viewed immediately or stored for later analysis. A flag at the umbilical connection on the aircraft indicated a propulsion system GO/NO-GO condition to the ground crew. The ground unit had the capacity to store and present more than 50 data records, normally 12 flights, and incorporated self-check capability. The DDU could be connected to a standard commercial teletype or a high-speed printer that printed out the displayed data.

Experience

To provide an environment in which the benefits could be quantitatively determined, maintenance personnel completed normal maintenance data forms plus an additional ATC special test form. This form documented and provided a narrative for engine malfunction reports, engine removals, troubleshooting, and repair maintenance manhours, as well as troubleshooting and trim fuel used for the EHMS and control engine groups. The comparative results are detailed in Table 12. The data once obtained depicted quite a different set of circumstances from what was originally expected. In the categories

Table 12

ACTIVITY SUMMARY FOR EHMS AND CONTROL ENGINES

	EHMS Engines	Control Engines
Number of engines	26	26
Total flight hours	6225.7	6442.7
Malfunction reports	97	48
Ground maintenance		
Unscheduled removals	53	23
Troubleshooting manhours	169.2	89.7
Repair manhours	1403.4	530.0
Engine ground runs		
Troubleshooting	52	38
Trims	26	14
Fuel used (gal.)		
Troubleshooting	4846.0	1786.0
Trims	5720.0	4480.0

of removal rates, maintenance, and fuel required, EHMS's engines consumed more resources than the control group did.

Although both engine groups had similar numbers of flight hours, Table 12 reveals major differences in all other categories compared. But in this analysis the proper normalizing value is malfunction reports, not flight hours. Because the malfunction report triggered in sequence troubleshooting manhours, repair manhours, engine ground runs, and engine trims, any comparisons of the events normalized to flight hours will contain this malfunction report cause-and-effect bias. Thus, by normalizing the events of interest on a malfunction report basis, the EHMS effect can be independently discerned. For example, a lower proportion of EHMS engine ground runs per malfunction report may indicate EHMS provided positive maintenance direction, which for a class of malfunction obviated the need for the ground troubleshooting run.

Once this conditional relationship between malfunction reports and follow-on maintenance is understood and accounted for, the path the analysis must take is clear. Those malfunction report situations described by a binomial distribution (engine removal, engine ground run, engine trim) should be statistically tested to determine if there is a significant difference between the EHMS and the control engines. For those events of interest that are not discrete (troubleshooting manhours/malfunction report, repair manhours/malfunction report, and fuel used/malfunction report), the method of analysis used the Smirnov goodness-of-fit test and the Chi-square (χ^2) statistics to determine if the EHMS and control distribution are homogeneous--i.e., have the same distribution. The Smirnov test is used to test for equality of the two distributions. This test is a very general one for any deviations from equality. We have also used the χ^2 test in testing the homogeneity of the distributions. The disadvantage of this test is that the data must be categorized within somewhat arbitrary class limits. Those selected were based on our experience and the requirements of minimum cell size for applying the test.

If nonhomogeneous distributions between the EHMS and the control engines are detected, the data will be analyzed with the intention of improving the quantitative understanding of EHMS's effect. When a significant effect of EHMS exists, and logic as well as insights from personnel involved with the program can proffer no alternative explanations, then the differences will be attributed to EHMS.

Engine Time Between Overhaul (TBO) and Operating Time Comparisons. We examined both TBO and engine flight hours achieved during Phase II evaluation distributions, because any difference in either statistic may explain all or part of the difference between the EHMS and control engines. Tables 13 and 14 summarize the data by engine serial number for the instrumented and control engines. In Fig. 1 the two TBO empirical distributions, Fn(X), are plotted. The Smirnov goodness-of-fit test is applied and no significant difference is found,

Table 13

EHMS TEST ENGINES

Engine Serial Number	Number Malfunction Reports	Unscheduled Maintenance Manhours Troubleshoot	Unscheduled Maintenance Manhours Correct	Flying Hours	Number of Removals	Ground Runs Troubleshoot Number	Ground Runs Troubleshoot Fuel	Ground Runs Trim NR	Ground Runs Trim Fuel	Checkout Number	TBO[a]
231796	5	11.0	192.0	288.1	4	2	211	2	440	1	2338
232715	2	4.1	134.0	179.0	1	0	0	1	220	0	1025
230321	2	2.5	16.6	246.7	1	1	90	0	0	2	0
231032	5	9.5	22.5	364.6	3	3	320	3	660	2	1021
232578	0	0.0	0.0	189.0	0	0	0	0	0	0	2054
232467	5	7.6	48.2	359.6	3	3	344	0	0	5	1318
232137	4	7.3	22.5	293.5	2	3	129	2	440	2	2095
231190	3	2.0	29.0	198.8	3	1	15	0	0	3	2149
230268	5	5.5	155.0	154.1	3	3	192	3	440	3	0
231260	1	1.0	2.0	290.3	0	0	0	0	0	1	1054
231735	8	12.0	52.0	326.4	3	6	555	3	660	4	0
232882	6	15.5	95.0	178.2	3	4	683	2	440	4	1767
230841	1	1.0	0.5	147.3	0	1	35	0	0	1	1478
231615	0	0.0	0.0	307.0	0	0	0	1	220	0	1164
230699	5	8.1	22.2	297.5	2	3	447	0	0	5	1966
232126	0	0.0	0.0	228.0	0	0	0	1	220	0	1093
231675	3	5.0	286.0	266.1	3	1	60	1	220	2	1805
231650	12	24.3	108.0	310.0	7	7	813	0	220	8	1208
230630	9	12.5	19.8	285.7	2	5	453	0	0	9	932
230662	1	0.3	46.0	243.7	1	0	0	1	220	0	188
232130	3	3.2	28.6	182.0	0	1	45	0	0	0	0
230790	4	2.3	12.5	235.6	2	2	100	1	220	3	0
231661	2	2.0	2.0	173.5	1	0	0	0	0	1	2006
231182	6	8.5	47.0	247.6	4	3	228	1	220	5	0
230947	4	24.0	52.0	152.5	4	2	95	3	660	1	1548
232655	1	0.2	10.0	83.9	1	1	31	1	220	0	1973

[a]Time Between Overhauls as of July 1976.

Table 14

CONTROL ENGINES

Engine Serial Number	Number Malfunction Reports	Unscheduled Maintenance Manhours Troubleshoot	Unscheduled Maintenance Manhours Correct	Flying Hours	Number of Removals	Ground Runs Troubleshoot Number	Ground Runs Troubleshoot Fuel	Ground Runs Trim NR	Ground Runs Trim Fuel	Checkout Number	TBO[a]
230369	4	6.3	12.0	309.5	3	4	123	1	320	4	2103
231788	3	4.0	9.0	363.0	1	2	93	0	0	3	2039
231605	3	4.5	4.0	398.7	1	3	92	1	320	2	1279
230573	3	3.0	28.0	413.9	1	1	63	0	0	3	201
231954	3	2.0	271.5	256.8	1	2	45	1	320	1	266
232027	1	1.0	2.0	321.3	0	0	0	0	0	1	1139
230242	0	0.0	0.0	196.1	0	0	0	2	640	0	1038
231150	1	1.0	0.0	359.5	0	1	50	0	0	1	1033
230995	1	1.0	0.5	150.1	0	1	31	0	0	1	2160
230868	1	0.5	4.0	91.0	0	1	31	0	0	1	2338
231211	2	6.5	30.0	336.2	2	0	77	1	320	1	1274
230439	3	4.0	31.0	422.2	2	2	187	2	640	2	2127
231946	1	1.0	0.0	265.1	1	1	90	0	0	1	1252
232741	3	5.5	55.5	236.5	1	3	143	1	320	2	1369
230465	2	3.0	5.0	398.4	2	2	122	0	0	2	396
232482	3	26.0	18.0	321.0	0	3	184	1	320	2	1137
232766	1	0.5	12.0	385.1	0	0	0	0	0	1	1013
230931	0	0.0	0.0	79.7	0	0	0	0	0	0	1064
232289	1	0.5	4.0	202.4	0	0	0	0	0	1	2141
232037	1	0.5	2.0	63.1	1	1	16	0	0	0	2258
230700	3	6.0	18.0	258.4	3	3	135	1	320	2	2148
230542	1	4.0	7.0	223.1	1	1	90	0	0	1	1091
231710	2	1.8	4.0	177.4	1	2	154	0	0	2	2234
230658	3	3.0	7.5	161.1	1	3	30	2	640	2	2109
231989	2	4.1	5.0	29.7	1	2	30	1	320	1	0
232341	0	0.0	0.0	23.3	0	0	0	0	0	0	0

[a]Time Between Overhauls as of July 1976.

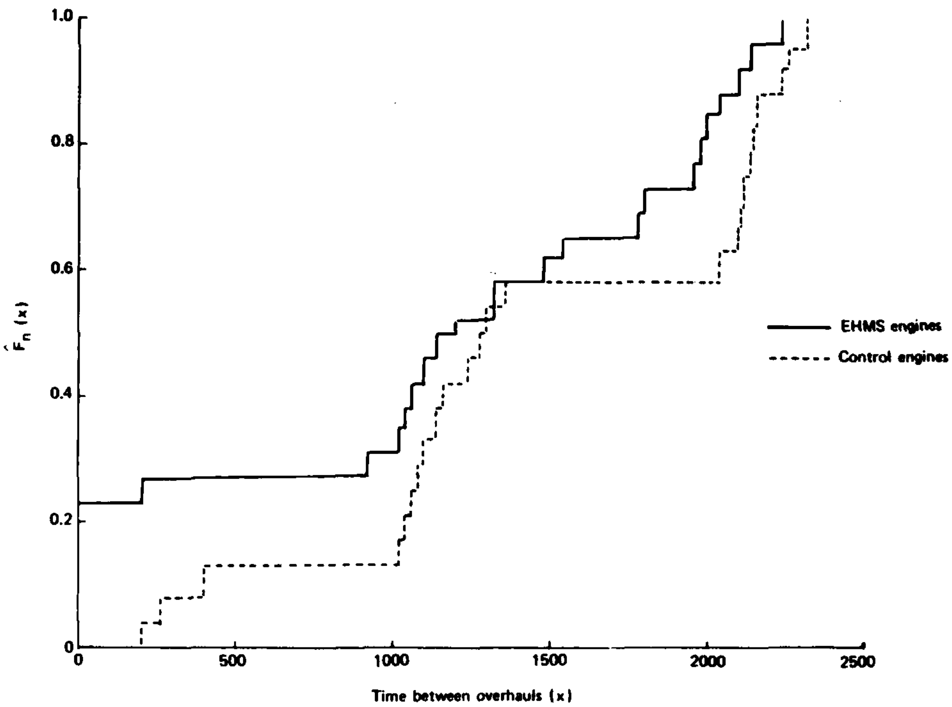

Fig. 1 — Empirical TBO distribution for EHMS and control engines

P value = 0.24.[4] An alternative χ^2 test proved not to be significant as well with a P value = 0.59. However, as Fig. 1 reveals, the distribution of the control engines lies below the empirical distribution of the EHMS engines.[5]

Similarly, both statistical tests reveal no significant difference between the EHMS and control engine flight hour distributions, Smirnov P = 0.31 and χ^2 P = 0.18. However, the EHMS engines accumulated flight hours at a faster rate; see Fig. 2.

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[4] The P-value (probability value) is significant whenever it is less than the level of significance specified.

[5] In the TBO analysis all engines initially in the control group were included, even though several engines left Randolph AFB prior to completion of the Phase II evaluation.

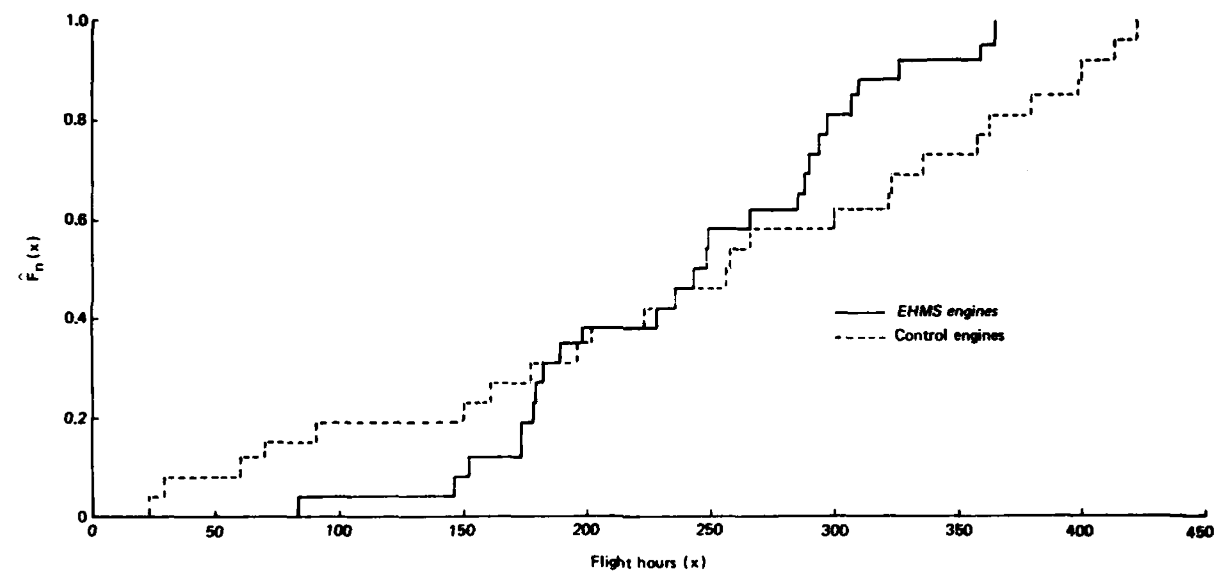

Fig. 2 — Empirical flight hour distribution for EHMS and control engines

The P values indicate that there is no reason to believe both engine groups are not homogeneous. When one knows that both groups of engines probably come from the same population, the data can be examined to determine the cause of the differences between the two groups.

Engine Malfunction Report (MR). Although there is no significant difference between the flight hours of both engine groups during the Phase II evaluation, there is a significant difference in the number of malfunctions reported (see Table 12).

When the flight hours per malfunction report are compared (see Table 15) the control engines experienced 108 percent more flight hours per malfunction report than did the EHMS engines. At this point in the analysis we will assume that EHMS caused this difference. We examine this assumption later.

Figure 3 identifies the Phase II engine malfunction reports by initiator: pilot, EHMS and pilot,[6] maintenance personnel, and EHMS

Table 15

FLIGHT HOURS PER MALFUNCTION REPORT

	EHMS Engines	Control Engines	P-value
Mean[a]	56.76	133.06	0.00
S.D.	39.27	80.11	

[a]Because the actual flight hours when the last malfunction occurred were unavailable, these values overestimate the true mean. However, we bebelieve the outcome would not be significantly altered.

[6] EHMS communicates no information to the pilot.

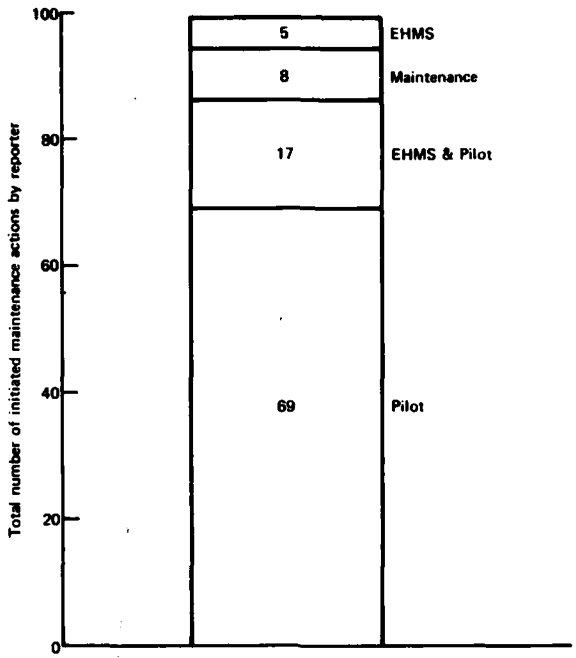

Fig. 3—Maintenance history engine malfunction report by initiator

alone. The data reveal the pilot as the most sensitive to engine malfunction, followed by ground maintenance crews, with EHMS contributing about 5 percent of the detections. When the follow-up maintenance actions are broken into categories, Fig. 4 shows that the pilot and ground maintenance crew account for all but one of the repair actions. EHMS uncovered five malfunctions--one requiring engine repair (an overtemperature unnoticed by the pilot), and four adjustments. In slightly more than a third of the pilot-reported malfunctions, EHMS did provide additional maintenance information to either confirm an engine problem or explain the true cause of the pilot complaint, such as engine stall caused by out-of-the envelope operation. The Phase II evaluations detected 75 percent of the malfunctions EHMS was designed to detect.

<u>Unscheduled Engine Removals (UER)</u>. Comparison of the proportions of unscheduled engine removals per malfunction report for both engine groups reveals no significant difference (see Table 16).

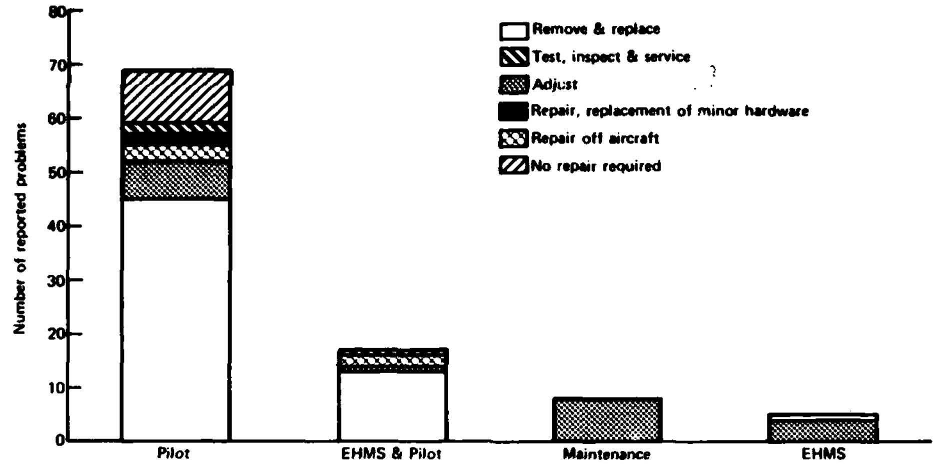

Fig. 4 — Maintenance action summary

Table 16

UNSCHEDULED ENGINE REMOVALS PER MALFUNCTION REPORT

	EHMS Engines	Control Engines	P-value
Proportion	0.55	0.48	0.21

Thus, we have the interesting observation that once a malfunction report reaches maintenance, the probability of that engine being removed is independent of engine type. This certainly is unexpected, especially when the malfunction reports of the EHMS-equipped engines are twice those of the control group. Nevertheless, the removals indicate that legitimate engine problems are being uncovered as a direct result of the malfunction reports.

Troubleshooting Manhours. Often the initial malfunction report is vague, identifying the effect rather than the cause of the malfunction. Troubleshooting manhours as defined here are the maintenance hours required to identify the malfunction's cause or conclude that there is no engine malfunction. Perhaps, as often was the case, the problem was a faulty gauge. Both the Smirnov, P = 0.20, and the χ^2, P = 0.16, reveal no major difference between the times required to troubleshoot the EHMS or the control engines; see Fig. 5.

Figure 5

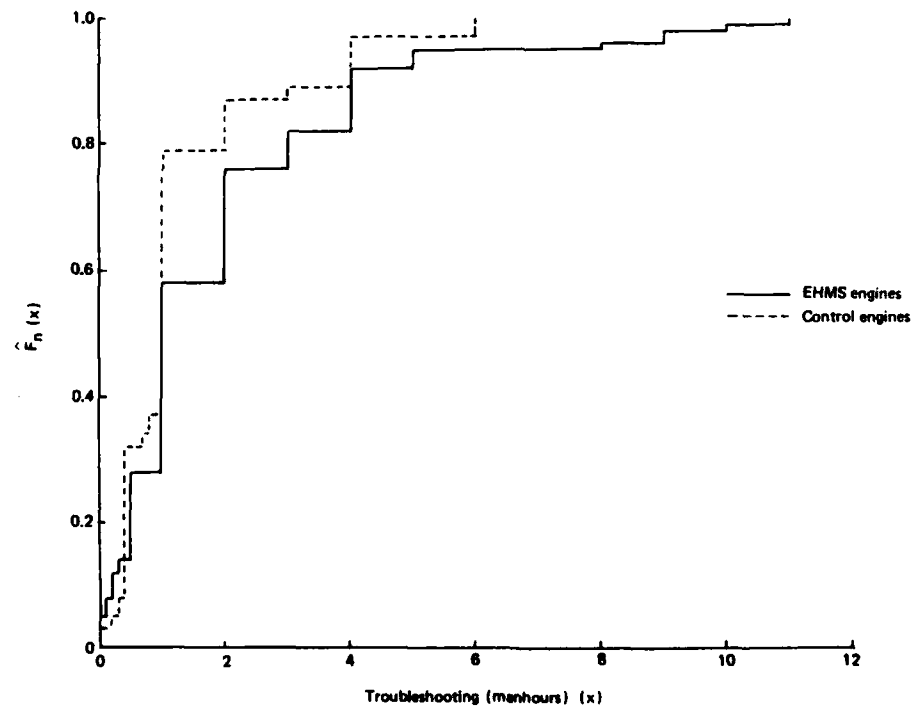

Fig. 5—Empirical troubleshooting manhour distributions for EHMS and control engines

Repair Manhours. Once the cause of the malfunction has been identified, the category repair manhours reflects the manhours to correct the malfunction and return the engine to service. As shown in Fig. 4, several repair codes e103st depending upon the type and extent of repair required. In this analysis only the "R" code, remove and replace, was examined. This limit was selected for several reasons: The other codes appeared infrequently, some required no maintenance actions, and others required skills or equipment not available to base maintenance.

Again the analysis shows no statistically significant difference for repair manhours spent per malfunction report between the EHMS and control engines, Smirnov P = 0.14, and χ^2 P = .22. Figure 6 does show that the EHMS distribution falls under the control engines. Thus, acting on the malfunction reports, maintenance is finding and correcting engine problems.

Ground Troubleshooting Runs. When the malfunction report does not clearly identify the cause, or maintenance wants to confirm the reported engine malfunction, the engine will be ground run in an attempt to troubleshoot the malfunction or duplicate the pilot complaint. Table 17 makes the comparison for the EHMS and control engines.

The significant difference between the troubleshooting runs per malfunction report can be explained, in part, because in several cases EHMS identified the cause of the apparent engine malfunction while the malfunction report only identified the effect as stated earlier. Possible examples are engine flameout caused by out-of-the-envelope operation, and errant cockpit gauges.

Discussions with the maintenance crews indicated that sometimes EHMS data provided sufficient understanding of the malfunction report to obviate the need for ground running. The low P value substantiates their views by indicating that a highly significant difference exists in the proportions of engine troubleshooting runs between the two groups. The 46 percent increase in control engine ground runs can be rationalized because less information defining the malfunction

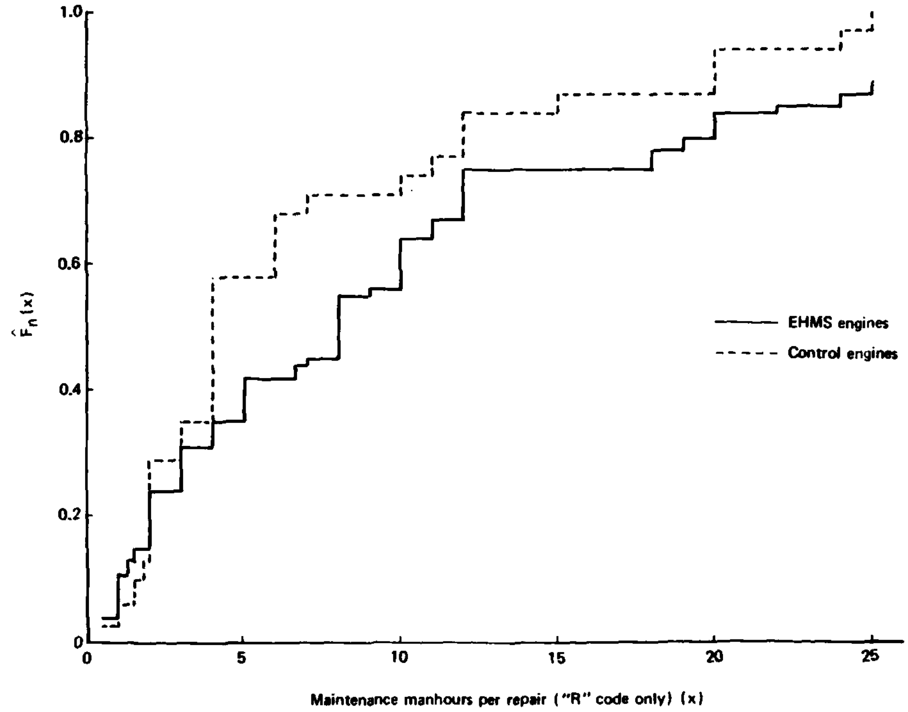

Fig. 6 — Empirical maintenance manhours per repair distributions for EHMS and control engines

Table 17

ENGINE TROUBLESHOOTING RUNS PER MALFUNCTION REPORT

	EHMS Engines	Control Engines	P-value
Proportion	0.54	0.79	0.00

cause is available. This additional frequency of ground running might be interpreted as the investment necessary to gain maintenance information similar to that provided by EHMS.

Troubleshooting Fuel. Fuel used per troubleshooting run also exhibits a significant difference between the two engine groups: Smirnov P =.08, and χ^2 P = 0.03. The EHMS engines required about 75 percent more fuel per troubleshooting run. This increase for the EHMS engines results because 29 percent of the EHMS engines used more than 100 gallons of troubleshooting fuel but only 4 percent of the control engines used that much fuel. Figure 7 shows the troubleshooting fuel use frequency distributions. (Of the eight occasions when more than 150 gallons of fuel were used, three resulted in maintenance being unable to verify any malfunction. The possible cause of this phenomenon--increased pilot sensitivity due to EHMS presence--will be discussed in a following section.)

Engine Trims. Adjustment of the engine fuel control is called engine trimming. Engines are trimmed to compensate, within limits, for thrust deterioration caused by foreign deposits, material erosion, and other items that affect air flow through the engine as it accumulates operating time. Engines are usually trimmed after repair or replacement of any of the gas path components to ensure that proper temperatures, rotor speeds, and stall margins are maintained.

A comparison of the manhours and fuel required to trim the two side-by-side installed engines (Table 18) indicates a labor and fuel savings of 2.5 manhours and 200 gallons for the engines with EHMS.[7] However, even though there is both an estimated manhour and fuel savings per trim, EHMS engines did experience roughly twice the number of trims, resulting in more total fuel used. On a trim-per-malfunction-report basis, there again was no detectable difference between EHMS and the control engines (Table 19).

[7] Both fuel and manhours were estimated by maintenance personnel.

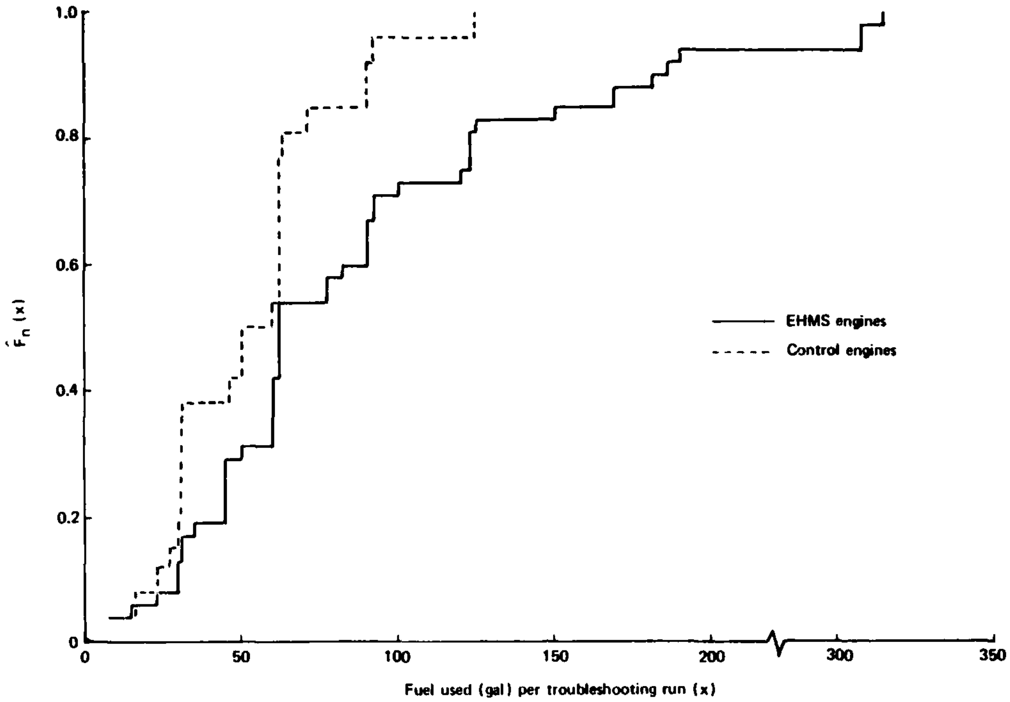

Fig. 7 — Empirical troubleshooting fuel used per troubleshooting engine run distributions for EHMS and control engines

Table 18

T-38 TRIM COMPARISON (BOTH ENGINES)[a]

Task	Manhours with EHMS	Manhours without EHMS
Set-up	.2	1.0
Engine run	1.0	1.2
Equipment removal	.2	1.0
Inspection	NA	.2
Engine re-run	NA	.5
	1.4	3.9

Labor savings = 2.5 Manhour/Trim
Fuel savings = 200 Gal/Trim[a]

[a]Fuel and manhours were estimated by maintenance personnel.

Table 19

ENGINE TRIMS PER MALFUNCTION REPORT

	EHMS Engines	Control Engines	P-value
Proportion	0.27	0.29	0.38

EHMS Engine Analysis. In order to better understand the effects of the additional maintenance information EHMS provided, EHMS engines were divided into two samples (see Table 20). The first group represented EHMS confirmed pilot-reported malfunctions for which it provided additional information and maintenance direction. The second group consisted of reported malfunctions where maintenance relied solely on the pilot's description of the malfunction. The objective was to learn if the EHMS data, which are in addition to data provided by the pilot, affected engine removals, maintenance manhours, troubleshooting or trim runs, or fuel used.

A comparison was made of the frequency distributions of troubleshooting manhours per malfunction report and maintenance manhours per malfunction report. The results revealed no detectable difference. (Troubleshooting manhours per malfunction report: Smirnov, $P = .46$; χ^2, $P = .22$; maintenance manhours per malfunction report: Smirnov, $P = .51$; χ^2 $P = .43$.) The underlying assumption was that the types of malfunctions were similar in that similar amounts of labor were required.

Tables 21 and 22 show that there is no significant difference within the EHMS engine group for either troubleshooting runs or fuel used. Note that what EHMS does not report often provides maintenance information having equal value to what it does report. This is true only where the maintenance crew has confidence in the diagnostic system, as was apparently the case with EHMS during the Phase II evaluation.

Table 20

SUMMARY OF EHMS ENGINE ACTIVITY

	EHMS-Aided	Pilot Only
Malfunction reports	23	60
Ground maintenance		
Unscheduled removals	16	31
Troubleshooting manhours	46.8	116.2
Repair manhours	404.1	849.6
Engine ground runs		
Troubleshooting	11	37
Trims	--	--
Fuel used		
Troubleshooting	1233.0	3152.0
Trims	--	--

Table 21

TROUBLESHOOTING ENGINE GROUND RUNS PER MALFUNCTION REPORT

	EHMS Engines	Control Engines	P-value
Proportion	0.48	0.62	0.12

Table 22

COMPARISON OF FUEL USED PER TROUBLESHOOTING RUN

	EHMS-Aided	Pilot Only	Test	P-value
Mean Fuel Used (gal.)	112.09	85.19	χ^2	0.18

Engine Flameouts. Early in the test program a decision was made to utilize the EHMS data to identify flameout incidents caused when the aircraft is flown out of the engine's operational envelope. The J85-GE-5 engine is susceptible to flameouts under the following combined conditions:

- Altitudes above 35,000 feet,
- Airspeeds below 250 knots,
- Rapid throttle movement.

ATC policy on flameouts occurring in the T-38 aircraft requires an extensive inspection when an engine experiences a one-time flameout. If the same engine experiences three flameouts within two hundred flight hours, the engine is disassembled, inspected, reassembled, tested, reinstalled, trimmed, and test flown.

In March 1976, ATC waived the inspection requirements when EHMS data showed the aircraft operated outside the flight envelope. Out-of-the-envelope operation occurred on three occasions during the test program. Northrop estimates a savings of 345 manhours for the three incidents (see Table 23).

Engine Overtemperatures. On three occasions during Phase II, EHMS reported engine overtemperatures (see Table 24). In only one of the three cases was the pilot able to estimate the magnitude and duration of the overtemperature. In the second case a severe overtemperature went unnoticed, and in the third a nozzle malfunction, which would imply an engine overtemperature, was reported. The unreported case represents the only EHMS detection resulting in an engine removal. However, the importance of this lone detection cannot be determined. Although inspection revealed severe turbine damage, maintenance personnel felt that the damage was so severe that either a preflight inspection would have discovered the damage, or a ground abort would have resulted, because the engine probably would not have started.

Table 23

COMPARATIVE MANHOUR DATA PER T-38 ENGINE FLAMEOUT

(A/C flown out of the envelope)

Maintenance Function	Manhours with EHMS	Manhours without EHMS	Manhours Saved[a]	Manhours Saved[b]
Inspections	0	20	20	0
Engine removal	0	9	0	9
Engine tear down	0	275	0	275
Test cell runs	0	5	0	5
Engine reinstallation	0	12	0	12
Functional check flights (FCF)	0	4	0	4
Total	0	325	20	305

Number of flameouts[a] 2 x 20 MH = 40 MH
Number of flameouts[b] 1 x 305 MH = 305 MH

Total MH saved 345 MH

[a]First or second flameout on same engine.

[b]Third flameout on same engine.

Table 24

PILOT-REPORTED AND EHMS-REPORTED OVERTEMPERATURES

	Pilot-Reported		EMHS-Reported	
Event	Temperature °C	Duration (seconds)	Temperature °C	Duration (seconds)
1	740	3-4	779	41
2	Nozzle malfunction reported		776	16
3	None reported		793	195

Findings

Even though the analysis focused on events per malfunction report, we must maintain the proper overall perspective. The malfunction reports for the EHMS engines were more than twice those of the control group for a similar number of flight hours. In addition, maintenance confirmed the validity of those reports by investing similar repair hours per malfunction report for both the EHMS and control engines. This similarity reveals that maintenance was finding and correcting legitimate engine problems. Were similar engine problems going undetected and not corrected in the control group, or was the maintenance effort expended on the EHMS engines over and above that required?

In order to gain additional insight into these questions, we made a final statistical test. The premise for the test was that if pilot sensitivity to engine malfunction is increased, then the number of malfunction reports for which maintenance could find no problem should also increase. Table 25 shows the test results. The results are moderately significant, but the final conclusion, of course, rests with the reader.

For the seven original Phase II objectives, the results are statistically significant for only two: maintenance manpower and

Table 25

TEST FOR PILOT SENSITIVITY

	EHMS Engines	Control Engines	P-value
Proportion of pilot-reported malfunctions for which maintenance could find no problem	0.12	0.05	0.12

fuel required. Clearly, the presence of EHMS resulted in more maintenance manhours and more fuel consumed for the EHMS engines. However, EHMS independently detected only five problems: four minor engine accessory adjustments and one severe overtemperature. These five EHMS-discovered events fail to account for the significant differences between the two engine groups.

The cause of the additional maintenance and fuel used is the increased frequency of malfunction reports. There are several plausible explanations for the difference between the number of malfunction reports for the EHMS and control groups. The most obvious is that the EHMS engines as a whole came from a different engine population that was more prone to malfunction. However, qualitative and quantitative examination produces no discernible difference among the engines.

ATC took care to ensure that the operational environments for both engine groups were, if not identical, similar. Variations in engine age can be eliminated as a cause as well, because both qualitative and quantitative analysis reveal no difference. There remains only one workable explanation for the difference. The additional attention to the EHMS engines causes the pilots to be more aware of engine operation, and they report more malfunctions. This increase in pilot sensitivity, although statistically unconfirmed, was alluded to by maintenance personnel as a possible cause of the increased malfunction reports.

The data on engine parameters monitored by EHMS represent only the first step in either long-term or short-term trend analysis. Currently, interpreting step changes or trends in an engine parameter is time consuming. A malfunction must be experienced and the data leading to the malfunction must be analyzed in order to reconstruct data trends that will signal an incipient malfunction. Concomitant with Phase II, trending analysis tools were being developed; therefore no engine malfunction was detected by trending EHMS data during the evaluation.

The J85 was a mature engine and the number of engine problems encountered during Phase II was not very large. Also, the EHMS was not a new system, having been through a feasibility phase (Phase I) during December 1972 and January 1973. Nevertheless, hardware and software problems in the EHMS caused schedule delays. A six-month delay was necessary to shake down the installation and software. The shakedown not only lowered the false-alarm rate but also reduced the EHMS maintenance manhours per flight hour below the number deemed acceptable for day-to-day operation.

MALFUNCTION DETECTION ANALYSIS AND RECORDING SYSTEM (MADARS)

Background

The C-5A MADARS is an operational in-flight test and analysis system monitoring a total of 850 airframe and engine parameters. Approximately 30 engine or engine-related parameters are recorded for each engine. The system was developed by the C-5A SPO and Lockheed Aircraft Corporation and is similar to a commercial airline Airborne Integrated Data System (AIDS), which monitors aircraft subsystems. The initial MADARS justification was maintenance cost reductions. MADARS holds a unique position among military engine condition monitoring systems, because it is the only military system incorporated into the initial aircraft specifications.

Technical Approach and System Description

All C-5As were equipped with MADARS during manufacture. The system was designed to detect malfunctions in selected aircraft systems and to record the malfunction as well as routine operational data on a magnetic tape. Engine parameters are examined by engine health subroutines during cruise. The cruise envelope is defined as an altitude of 20,000 ft or above, mach number of 0.4 to 0.8, and an engine pressure ratio above 4.0. When steady-state engine operation is achieved, the parameters of interest are compared with standard values and deviations are computed. If the deviations exceed stored limits, the values are printed out for the flight engineer; otherwise

they are simply recorded. The system can be operated in two modes--automatic and manual. The automatic portion operates continuously. The manual portion is used at the discretion of the operator. During manual mode operation, the automatic mode is uninterrupted. Using the manual mode the operator, a member of the flight crew, can diagnose malfunctions using stored preprogrammed procedures. After landing, the data that were recorded on magnetic tape in the automatic mode are transmitted through dedicated, high-speed communication lines from the base to a central data bank at the Oklahoma Air Logistics Center, Tinker AFB, Oklahoma. The Ground Processing Station (GPS) at Tinker AFB comprises three tandem-harnessed IBM 360/65 computers that allow a nearly real time interchange of data. At the present time a fourth central processor is being added.

The flight data are analyzed and maintenance forms are generated automatically for malfunctions that meet certain criteria. Other maintenance requirements identified by visual inspections or other methods are coded and entered into the data bank, as are engine data obtained from test cell runs and spectrographic oil analysis. In this way the GPS data bank is kept complete and current. Computer displays and keyboards are located in the work areas so the maintenance technician has immediate access to historical data necessary for troubleshooting or documenting the malfunction.

Experience

As with all complex systems, MADARS suffered early reliability and availability problems and the inherent resistance to change that any new and different approach must overcome. Initially, MADARS was not a mission essential system; but as confidence, reliability, and availability grew, it was designated mission essential. Although the system has matured, as indicated by an improvement in the invalid to valid ratio, some of the desired detection capabilities have yet to reach maturity.

The benefits of MADARS/GPS fall into three categories: operational, maintenance, and engine management.

Operational. For sensitive overseas operations, having a measure of engine health as a guide to aircraft selection is important for two reasons: first, to improve the probability that the mission can be completed and the cargo delivered, and second, to avoid the often difficult logistic problem of engine repair or replacement at a remote overseas site. The operational advantage provided by having a large, nearly real time data base that accurately provides data on engine performance enables judicious selection of those aircraft whose engines are meeting performance levels and have significant useful life remaining to be selected for overseas missions. However, if aircraft requirements conflict with scheduled engine inspections, the MADARS/GPS provides data on which a decision can be made either to authorize continued aircraft operation or to conduct the inspection as planned.

Maintenance. Because data are available shortly after the flight has landed, MADARS/GPS has proven to be a useful trouble-shooting aid. Engine parameters can be analyzed not only for the most recent flight but as far back as needed before the failure. Thus, a trend of events or engine parameter shifts that led up to the malfunction can be used to predict future maintenance and schedule it at a convenient time and place. After maintenance has been performed, MADARS/GPS data have proven useful in assessing the effect of maintenance performed--i.e., it did or did not correct the problem.

The TF39 engine has evolved from the original -1 to the -1A and the current -1B configuration with a -1C model being considered. The -1A model was operated with a staged time-between-overhaul (TBO) of up to 3000 hours. The MADAR system permitted a more rapid development to the -1B configuration with a 5000-hour TBO than otherwise might have been possible. This extension was based on performance data available through MADARS/GPS, inspections, and required replacement at a mid-interval inspection of some hot-section components and fuel pumps. The -1C version will not have a fixed depot interval but will rely on MADARS data, inspections, and spectrographic oil analysis to dictate when maintenance is required. This on-condition

maintenance approach will have parts time or cycle limits permitting the engine to move away from the fixed-time overhaul intervals.

Management. Considering the military worth of the C-5A fleet, it is not unrealistic to expect MADARS/GPS to be used for the management of the engine inventory, spares, and scheduling of maintenance. In fact, some of the major benefits perceived by MAC and squadron maintenance personnel are in improved engine management that MADARS/GPS data permit. As experience has been gained in interpreting the data and associated trends, the expected engine maintenance work package and parts required can be planned for with a high degree of confidence, with the effect that time-consuming engine maintenance surprises, although not eliminated, are reduced. The improved awareness of engine condition also permits scheduling engine maintenance when recognized incipient trends begin to develop. Because the system is nearly real time, and data are readily available, consumption rates and MTBF for a given part are current and available to all having access to the system. This individual part analysis is useful in detecting deterioration or improving trends.

The inherent flexibility and comprehensive data available permit higher authority, through terminal access to GPS, to answer for themselves such questions as status of a given Time Compliance Technical Order (TCTO) without burdening organizational, intermediate, or depot maintenance personnel. Senior management can also compare bases or organizations with regard to the efficiency of their maintenance policies and procedures. Chronological maintenance history for each engine can be generated to determine if an extant problem is recurring or if the engine recently received similar maintenance. Standard engine programs as well as special purpose programs can be used to generate and analyze data of interest.

Findings

The most important lesson learned is that of system flexibility, and the awareness of the large support requirements--people, computers, and facilities--demanded by a real time monitoring system

that supports 78 aircraft and about 400 engines. MADARS/GPS was developed to reduce maintenance costs, but the prodigious amounts of raw data collected and stored in a retrievable form have proved useful in ways unimagined by the original system planners. Having the raw data readily available allows a tailoring of system outputs to individual formats perceived most useful by each user. Although the system is simple to use, its sheer size and the fact that it is a computer system cause some to shy away and not realize the system's full capability.

The most useful aspects of MADARS are:

1. All information pertaining to the engine is in one data base--the Engine Configuration Management System--which keeps track of where and when critical items are installed and what remaining life can be expected from the components, either in hours or cycles.
2. The engine subroutine program, which allows flight crew and operations personnel to predict whether a projected mission can be accomplished without exceeding parameter limits. In addition, maintenance personnel can plan removal of engines because of low performance.
3. A 90-day history of past maintenance performed on installed engines is available for engine managers to aid in evaluating engine problems.
4. A complete flight history is available to give a second-by-second account of engine performance during flight. Data are provided on the most important engine parameters as well as approximately 23 other readings. This provides sufficient information to eliminate many unnecessary removals.

Significant problems are:

1. Inadequate hardware in the vibration system, causing errors in data recorded. The only solution is to acquire improved hardware. (Recent developments point in that direction.)

2. Adequate user instructions that will instruct engine managers both as to what is available and how it should be used. At the start, it was realized that changes would accrue very rapidly; thus written procedures were allowed to take a back seat to development.
3. The MADARS/GPS System, during its early development years, was subordinate to Air Force automation programs. In recent years, the C-5 MADARS/GPS has come to the foreground and the only management procedures are written with the Military Airlift Command and do not apply within other using commands (i.e., AFLC engine managers).

Because all the C-5As were initially outfitted with MADARS, there is no control group against which outcomes can be compared.

IN-FLIGHT ENGINE CONDITION MONITORING SYSTEM (IECMS)

Background

As a result of a number of A-7 airplane losses due to engine malfunction, the U.S. Navy became interested in an In-flight Engine Condition Monitoring System (IECMS) initially for safety reasons. Beginning in October 1971, the Navy conducted a comparative evaluation of two prototype installations. Detroit Diesel Allison Division (DDAD) of General Motors, manufacturer of the A-7E engine (TF41), and Pratt and Whitney (P&W), manufacturer of the A-7B engine (TF30), submitted proposals to develop in-flight engine monitoring systems for their aircraft. DDAD subcontracted the electronics to Teledyne Controls Division of Teledyne Systems. P&W contracted similarly with Hamilton Standard Division of United Aircraft. The evaluation was completed about mid-September 1972, with the DDAD system being selected for preproduction service evaluation.

Technical Approach and System Description

The justification for IECMS was to reduce engine-caused aircraft losses by at least 50 percent.[8] A combination of pilot in-flight warning through cockpit lights, visual flag display panel to alert maintenance crews to engine malfunctions, and computerized trending and data analysis are used.

A total of 21 transducers have been installed on the TF41-A-2 engine for the measurement of temperatures, pressures, etc., necessary for diagnosing engine operation[9]; 24 additional sensors relating to switch postion, amperage, voltage, etc. are wired into existing engine components. IECMS is a dedicated system requiring an aircraft modification to incorporate additional sensors and the data monitoring and tape storage unit. Eleven additional inputs are obtained from airframe-mounted components such as fuel valves, landing gear.

The system is composed of two categories of equipment: The airborne portion monitors engine operation and automatically records data during selected flight modes (engine limit exceedances and transient engine conditions); and the ground station computer analyzes the data recorded by the airborne system and outputs engine status or required corrective maintenance actions. The data are also trended to detect engine deterioration, which indicates required maintenance or incipient engine malfunction.

Airborne. The airborne components consist of:

1. Engine/airframe sensors

[8] Since then the maintenance aspects have become more important, particularly with the advent of the planned Navy Engine Analytical Maintenance Program (EAMP).

[9] The original system design was driven by flight safety, causing measurement of many parameters that might not have been required if the original use was maintenance-oriented.

2. Engine Analyzer Unit (EAU)
   --Signal Analyzer section requiring engine and airframe input signals
   --Data Management section controlling data flow to the Tape Magazine Unit (TMU), cockpit indicators, or Flag Dislay Unit
3. Flag Display Unit (FDU) displaying limit exceedances to the ground maintenance crew
4. Tape Magazine Unit (TMU) storing data from the EAU on command.

Ground Station. The ground station and its software process data received from the TMU, output status of the engine, and identify the maintenance actions required.

The ground station components are:

1. Tape Interface Unit (TIU)
2. Ground Computer Unit (GCU)
3. Computer Control Console (CCC)
4. Mass Storage Unit (MSU)
5. Line Printer Unit (LPU)
6. Tape Drive Unit (TDU).

The Ground Support Equipment (GSE) includes that equipment required to maintain the airborne and ground hardware. An Engineering Readout Unit (ERU) provides a visual readout of the parameters in engineering units during an engine ground run. A Signal Simulator Unit (SSU) simulates an engine or airframe IECMS parameter for bench checks of the airborne software or hardware.

Experience

An analysis that compares IECMS-equipped engines directly with non-IECMS engines is difficult, if not impossible, because of operational history of the TF41 engine. After introduction into the fleet in 1969, the TF41 engine performed well until early 1972, when

it began to experience difficulties. As recently as mid-1975, a hard-time Hot Section Repair (HSR) interval of 225 hours was established. Since 1972 the engine has received close maintenance attention and has experienced frequent inspections and removals. All these considerations overshadow the effect of IECMS. Therefore, IECMS is examined without any attempt to compare IECMS and non-IECMS equipped engines. Our objective will be to discern the effect, difficulties, and perceived benefits associated with using a large comprehensive engine condition monitoring system on a high-performance turbofan engine.

Early during development, a Navy evaluation stated, "The inherent capability of the IECMS to obtain instantaneous and accurate flight engine data for detail engineering analysis is a by-product that both complements and enhances its ability to perform in-flight engine condition monitoring."[10]

During a 1973 review, a preproduction evaluation was recommended. The evaluation began in August 1973 and continued through January 1974, with the recommendation that IECMS production be delayed because several key software routines were not operational and a high false diagnostic rate--about 5:1--necessitated verification of all diagnostics with engineering data by on-site contractor personnel. After contractor verification, the actual maintenance action sent to the squadrons was valid in 23 of 27 instances (85 percent). As the evaluation progressed, the number of invalid indications decreased markedly, but there was general agreement that this preproduction evaluation was premature.

IECMS development continued. A second evaluation began in July 1974 and ran till December 1974 at NAS Lemore and aboard the USS Enterprise (CVA(N)-65). The conclusions reached during this evaluation were similar to the first: no recommendation of a high-rate procurement until reliability was improved and the ratio of invalid to valid (22:12) diagnostics was improved. In addition, concern

[10] NATC Technical Report ST-136R-73, A-7 In-flight Engine Condition Monitoring System Evaluation, 14 August 1973.

surfaced as to the ability of Navy personnel to operate and maintain IECMS. This review, like the first evaluation, reported, "The system has demonstrated its potential to be a very valuable maintenance and flight safety tool."[11]

The most recent evaluation of IECMS was conducted by Commander, Operational Test and Evaluation Force (OPTEVFOR), in a report dated 28 February 1978. The evaluation criteria as specified by the Chief of Naval Operations (CNO) were:

1. The safety of flight engine discrepancy detection probability shall be at least 50 percent.
2. Diagnostic validity ratio shall be at least 0.80.
3. MFHBF (Mean Flight Hours Between Failure) of the TMU and EAU/FDU shall be at least 200 hours.
4. MFHBF for the sensor package and cockpit indicators shall be at least 300 hours.
5. MFHBF for the total airborne system shall be at least 100 hours.
6. MTBF (Mean Time Between Failure) for the Ground Station shall be at least 300 hours.
7. The ratio of IECMS TF41 engine removal rate to the basic TF41 engine removal rate shall be 0.85.
8. DMMH/FH (Direct Maintenance Manhours per Flight Hour) for IECMS TF41 will be less than that of the basic TF41.

The evaluation criteria divide into two categories: (1) IECMS equipment capability--criteria 1,2,3,4,5, and 6--and (2) IECMS effect on engine support--criteria 7 and 8.

The results of the 1976-77 USS Enterprise deployment found IECMS not satisfying these criteria (see Tables 26 and 27).

[11] A-7E Inflight Engine Condition Monitoring System Preproduction Evaluation, NAILSC, Patuxent River, Md., 10 January 1975.

Table 26

IECMS COMPONENT RELIABILITTY

	1976-77 Enterprise Deployment	
Component	MFHBF	Criterion
TMU	383	200
EAU/FDU	88	200
Sensor package	575	300
Cockpit indicators	766	300
Total system	59	100

Table 27

IECMS MAINTAINABILITY

	IECMS Engines	Standard Engines
DMMH/FH	1.12	0.80
Removal rate/1000 hr	1.74	1.85

The OPTEVFOR analysis was limited on several counts: (1) The evaluation failed to consider or apply any statistical methods that would have placed both the reliability and maintainability results in proper perspective. For example, determination of the removal rates was based on four IECMS engine removals and six standard TF41 removals--not nearly a large enough sample to have decisionmaking confidence in the quoted values.

In marked contrast to the OPTEVFOR evaluation, the report submitted by the Commanding Officer of Attack Squadron TWENTY-SEVEN is quite different in tone and content. The squadron report is more pragmatic in its evaluation of IECMS and reports on system effectiveness: "The planned product (IECMS output) is the realistic and, heretofore, elusive goal of providing the pilot and maintenance personnel of a single-engine aircraft with immediately usable safety of flight and go/no-go information. The information for the quick-look use is neither generous nor sparse, but a simple, timely and final presentation of only essential information."

On the false alarm note: "Airborne safety-of-flight false alarms (there were four) are an unacceptable, two-fold hazard. On one hand, their occurrence, however seldom, greatly erodes system credibility, significantly reducing system usefulness. On the other hand, in the shipboard environment, the resultant emergency pull-forward and crisis handling of aircraft on the flight deck create a definite safety hazard."

On system usefulness:

> In far too many instances, organizational troubleshooting to a proper depth, with current procedures and test equipment, is too difficult, time-consuming or, often, impossible. Presented with such a troubleshooting task, the technician/mechanic is forced to resort to a method frequently dubbed "shotgun troubleshooting." To make up for a lack of maintenance time, test equipment deficency or lack of expertise, the maintenance man "shot guns" by making an illfound, only slightly-educated guess, and, then, changing a component or making an adjustment. Because the action was inconclusive from the start, the next generation of the whole system is really more troubleshooting, rather than a confident system repair proof. Such "shot gun" methods are very costly; good, serviceable spares are changed, manpower is wasted, system repair may be prolonged and adequate repair may never be performed.

IECMS did prove beneficial in identifying equipment and operator problems. For example, IECMS reported 100 valid engine start malfunctions, 42 resulting from low air pressure or volume supplied by the ground starting equipment.[12] Operator problems, such as attempted starts with the manual fuel-shutoff valve closed and opening the fuel valve at too low an rpm, were also identified.

IECMS-equipped engines have experienced a reduction in removals for several engine accessories and controls at the expense of a higher adjustment rate, attributed to a closer monitoring by maintenance personnel. IECMS has also identified failures (one side of the ignition system needed for in-flight high altitude relight) that were going undetected within the fleet.

Findings

How to quantify the long-term design benefits of IECMS is a difficult task and is best illustrated by examination of three areas important over the long term. These are: the Component Improvement Program (CIP), engine testing, and future engine design. The CIP phase begins when the engine is introduced into the operational inventory and continues throughout the useful life of the system. When an engine is exposed to its operational environment and method of usage, material and design deficiencies become evident. However, frequently because of the paucity of engineering data, the cause-and-effect relationship is obscured. IECMS data have contributed to CIP in engine control systems, engine performance deterioration, low cycle fatigue, and components and parts useful lives.

On several occasions failure modes experienced by operational engines could not be duplicated in the test cell. IECMS continuous recordings were utilized to establish mission profile and engine duty cycle data, which led to a better understanding of the operational environment and an improved engine test cycle. Testing the engine to the IECMS test cycle did result in a duplication of the fleet failure modes and enhanced the engineering and design solution. These more

[12] Slow starts cause some hot-section distress but not generally engine removal.

representative test cycles permitted the new design to be tested to more realistic cycles and produced a higher confidence in the design solution. DDAD is currently using the IECMS data and the understanding (in terms of operational environment and parts useful life) it affords in their advanced turbine engine design efforts.

AIRBORNE INTEGRATED DATA SYSTEMS (AIDS)

Background

AIDS is a commercial, on-board automatic testing system that electronically monitors the performance of various aircraft systems during all flight modes (Fig. 8). Although AIDS, like MADARS, monitors mechanical (engine, hydraulics, control surfaces, etc.), electrical, and electronics systems (autopilot, inertial navigation, etc.), the following case study will focus on the propulsion aspects of AIDS as experienced by TWA on its B-747 and L-1011 fleets.

Initially, commercial justification of AIDS has been based on a combination of reduced engine operation and support costs, and improved flight safety. Application of engine condition monitoring

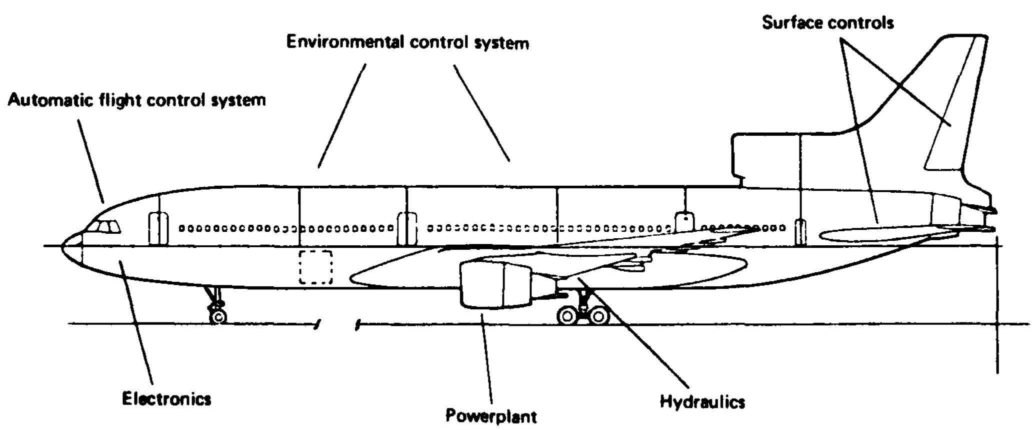

Fig. 8 — Aircraft subsystems monitored

at TWA began in the 1960s when the flight engineer manually recorded specific engine parameters. The recorded data were then forwarded to a central processing center in Kansas City to be trended and analyzed. The data then, as today, served as one of many inputs to maintenance personnel in planning and scheduling engine maintenance. As engine complexity and costs increased, TWA began using an electronic recording system aboard its DC-9 fleet. This system monitored a total of 52 airframe and engine parameters. Although the current concept and objectives of AIDS remain unchanged from the DC-9 application, engines continued their increase in cost and complexity while the design of the airborne and ground processing equipment matured appreciably, and the cost of data processing plummeted. These developments have afforded the flexibility to monitor the engine and airframe parameters necessary to initiate on-condition maintenance and maintain the safety margins required. The present AIDS system monitors engine parameters as well as other parameters necessary to calculate standard day conditions.

AIDS furnishes a new and additional source of data to TWA's propulsion engineers. The system was not designed to provide information to isolate individual part failures or independently generate work orders. The objective is to inform the engineers about malfunctions observed and individual engine trends developing. The engineer must then decide on the degree and extent to which further action is warranted. Follow-up action, if required, can range from immediate engine removal, to initiating line maintenance, to scheduling repair, to continuing close observation. At present TWA has 11 B-747 and 30 L-1011 aircraft equipped with AIDS.

Technical Approach and System Description

The transition of AIDS from a fondly embraced concept to a reliable operational tool was neither easy nor inexpensive for TWA, and the normal development problems associated with any advanced avionics systems and their integration were compounded by inherent resistance to change and the commercial pressures for an early positive return on investment. In fact, AIDS has been removed from

several other airline widebodies because of initial system problems, low reliability, and cost. It would have been removed from TWA's widebody fleet if AIDS did not feed the Digital Flight Data Recorder (DFDR), the FAA-required crash recorder. Because of the dependency of the crash recorder on AIDS, TWA had no choice but to make the system work. Once AIDS was in place and mature, economic justification for additional capability was straightforward. However, no airline would consider retrofitting an AIDS system because of the installation cost and opportunity cost of not having the airframe available.

The specific items making up the AIDS/DFDR airborne system are as follows:

Central Electronics Unit (CEU)--a computer that controls and synchronizes all other AIDS/DFDR units, according to a preplanned computer program.

AIDS Control Unit (ACU)--commonly referred to as the "AIDS Data Entry Panel (DEP)"--provides for selected pilot input, control, and monitoring of the system.

Data Acquisition Unit (DAU)--acquires parameter analog data, converts it, and formats it into digital form for transmission to the CEU.

Continuous Loop Recorder (CLR)--provides storage for the preceding five minutes of data from all parameters. Maintenance data are obtained from this unit for transfer to the Incremental Recorder on command by the Flight Engineer, and limit exceedance.

Incremental Recorder (IR)--a bulk recorder records only when instructed by the CEU. Provides permanent storage for both trend and maintenance flight data.

Digital Flight Data Recorder (DFDR)--a crash-protected, continuous loop recorder that provides 25 hours of storage of FAA-required flight recorder parameters.

A Built-In Test Equipment (BITE) function is incorporated in each of the AIDS/DFDR units except the Control Unit. The CEU monitors all of these BITE inputs during a self-test routine.

Daily, TWA transmits each aircraft's data into the central processing center at Kansas City. There are five remote data terminals at the major line stations. The terminal can transmit all of that day's aircraft data or selected flight-leg data for prompt analysis. All the data gathered over a 24-hour period are batch processed. Daily reports are then generated and available for engineering review and analysis.

Experience

Once the system began furnishing flight data, a great deal of data were available to aid in achieving the original airline objectives. The highest priority assigned to the use of AIDS data is the prevention of catastrophic engine failure. The powerplant has proved to be the most trendable of all systems monitored. Engine stalls are by far the most difficult to trend, but deterioration of engine components that lead to engine malfunctions is trended. These problem components have been replaced or corrected before severe malfunction could cause an incident.

AIDS has increased engineering know-how by an improved understanding of the cause-and-effect relationship between the events that cause a failure or an engine to malfunction. Most important, AIDS provides information upon which action may be taken (or initiated). But unfortunately, these benefits take time to develop. Experiencing failures, and reviewing the data leading up to the failures, precedes any attempt to correlate a particular trend with an incipient engine failure. Because of the insight AIDS has provided, engine design deficiencies have been identified, understood, and corrected.

Although catastrophic failure avoidance has been a primary focus, cockpit crew performance monitoring has proved to be a major and unexpected benefit. The data provided allow assessment from the safety perspective of crew skill and proficiency levels.

One of AIDS' benefits is the ability to test engine performance after repair or module replacement while the engine is installed. This elimination of test cell runs has improved turnaround time, reduced test and maintenance manhours, and lessened capital investment for minor repairs.

Findings

TWA's experience has been that the powerplant best lent itself to an AIDS approach. Powerplants, with their various pressures, temperatures, and rotating speeds, project a clear picture of detectable wear and provide signals of incipient failures due to deterioration of various engine components.

The proper use of the engine during all ground and flight modes has proved to be of considerable aid in changing those flight procedures that unnecessarily consume useful parts life and lead to engine malfunction. TWA has done considerable work on aerodynamic improvement of the L-1011 fleet. In the area of engine monitoring, the proper use of the engine's power to achieve the highest level of performance and economy becomes almost as important as engine failure in the commercial environment.

Exception Reporting Concept. As the propulsion group analyzed daily reports, one recurring problem arose: Major engine malfunctions occurred when AIDS was not in the process of automatic recording. The flight crew can manually initiate AIDS data recording so that information from the history recorder will become a permanent record; but the pilot's attention and efforts are concentrated on dealing with and correcting the in-flight malfunction, so not all the available data was always recorded. The end result of this problem was the introduction of exception recording. Parameters for an out-of-limit condition could be monitored and the amount of information transferred from the five-minute history recorder controlled so that only data directly related to the out-of-limits condition becomes a permanent recording. Recorded data demanded upon the detection of the limit exceedance will also generate a picture of the condition before, during, and after the malfunction or failure. This

technique, using the new solid-state history recorder vs. the previous mechanical model, has resulted in substantial improvements in engineering understanding.

Faster Reaction. TWA's ground system was designed for batch processing, so that when an aircraft problem needed immediate attention, data access and retrieval were impossible. The ground software has since been modified to enable engineering to receive data printouts processed on-line. With the improvement of high-speed data lines and the installation of computer terminals at most major line stations, the data are readily available to the engineering staff.

Additional Parameter Capacity. Ground software flexibility with various scan lengths is difficult to achieve. Many aircraft of the same fleet, in operation with different software packages and producing variable length scans, proved to be unwieldy. At times, dropping the monitoring of a parameter group to enable the monitoring of a new group is not a valuable tradeoff. So, along with the incorporation of data frames, the airborne software has blank fields where additional information may be added without altering the overall length of the data frames.

Flexibility and Adjustment. Because the on-board computer has core storage, the sampling of parameters is extremely flexible and permits the installation of new parameters with minimum effort. This is imperative so that parameters of little or no value may be replaced with others that may provide new insight to engine performance.

Calibration of Sensors and Instruments. The majority of cockpit instruments have a separated buffered output to AIDS. This can present problems when the instruments are calibrated. The general calibration procedure does not lend itself to the accuracy required by AIDS. For example, in the L-1011 Turbine Gas Temperature (TGT), the manufacturer's procedure calls for calibration over the full 1000°C range, but the temperature range most useful for engineering analysis is 700 to 750°C. The manufacturer calibrated over the full range and to a tolerance of +5°C. For the flight crew, this level was more than acceptable, but not for AIDS. The manufacturer's

procedure was rewritten to maximize the instrument accuracy in the 700 to 750°C range with an accuracy of +0.25°C.

Failure Prediction. Failure prediction is always listed as one of the goals of AIDS and an area of substantial payoff. But failure prediction is useful only if the underlying degradation rate is slow. It is more important to identify a parameter trend that indicates the component is coming into a critical region where failure may happen, and then take action to eliminate or lower the risk.

TWA's experience is that the AIDS-provided proof of failure often leads to a better understanding of the synergistic effects of individual component failures. The availability of engine operational data has resulted in studies on specific engine problems: auto-accelerations, stalls, vibration, and starting. The engine manufacturers have made great use of the TWA data.

ENGINE USAGE MONITORING SYSTEM (EUMS)

Background

The British developed the Engine Usage Monitoring System (EUMS) for application to the wide variety of fixed-wing, rotary-wing, and VSTOL aircraft operated by the Royal Air Force, the Royal Navy, and the Army. The initial objectives of EUMS differ substantially from those of U.S. engine monitoring programs. As with other recent engine monitoring programs, EUMS owes its conception to escalating operation and support costs of systems and subsystems and to the continuing occurrences of serious engine operational problems. These problems can be traced to inadequate understanding of complex engineering designs and the effects of changing mission requirements and operational use.

The British approach does not place prime emphasis on aircraft readiness. The motivation for the U.K. military forces is to ensure that training requirements are satisfied, NATO commitments kept, and optimum safety margins maintained. Therefore, their original engine monitoring system accumulated quantitative information about actual continuous engine use with the longer-term objective of reducing the

cost of engine ownership through improved engineering. Their goal was to achieve optimum useful lives of major rotating components through understanding the extent of deterioration and life remaining from thermal and Low Cycle Fatigue (LCF), creep, and thermal shock.

At present, the British efforts are on fatigue arising from a low number of cycles at high stress levels. LCF differs from most other failure modes in that precursor evidence of impending failure--which for other failure modes can be detected by boroscope, disassembly during overhaul, or repair--is not evident until actual crack initiation, which is then followed by rapid crack propagation, leading to catastrophic failure. The LCF phenomenon first became troublesome for the British on civil aircraft using automatic landing devices.[13]

> When analyzing flight recordings it was found that the autoland was continually adjusting the throttles during landing approach, and the effect of these small rpm excursions at high rpm levels was having a large effect on the total number of centrifugal stress cycles. These small cycles, when added to the major cycle produced by the basic zero-max-zero rpm excursion, were severely overstressing the engine with resulting failures.

The British recognize that useful life is determined by the aircraft's operational mission and power level transients, which vary unpredictably from sortie to sortie. Possessing no better tools for assessment of useful life remaining, the British, like the Americans, have established conservative intervals between scheduled maintenance.

The current British approach, initiated in 1974, pioneered by the Department of Engine Development Ministry of Defence MOD(PE), and assisted by Rolls-Royce, uses a continuous recording system on a small but increasing number of RAF aircraft (see Table 28).

[13] Michael Ferguson, Advances in Cycle Life Monitoring of Critical Engine Components, Rolls-Royce, Bristol, England, n.d.

Table 28

CURRENT, PLANNED, AND PROPOSED EUMS APPLICATIONS

Aircraft	Currently Instrumented	Planned	Proposed
Lynx helicopter	3		
Vulcan	3		
Jet Provost	3		
Jaguar	5		
Hunter	2		
Harrier	4		
Phantom	3		
Victor tanker	2		
Sea Harrier		4	
Lynx		5	
Sea King		3	
Buccaneer	3		
USMC Harrier			8
Hawk			6
Tornado			12
VC10			2
GNAT	4		

The recording system records a minimum number of parameters as contrasted with the current U.S. EDS programs. Below is an example for the Harrier.

HARRIER EUMS PARAMETER TYPES

Shaft Speed (NL)
Shaft Speed (NH)
Outside Air Temperature
Altitude
MN or Airspeed
Jet Pipe Temperature (0-500°C)
Jet Pipe Temperature (0-1000°C)
 (exhaust gas temperature)
Throttle Position
Nozzle Angle
Water Injection Switch

Technical Approach and System Description

To ameliorate the LCF problem, a dedicated recording system was developed that monitors every rpm excursion through the flight. This system was installed on a small sample of the aircraft population and continuously records the parameters listed above. When coupled with carefully recorded manual records of sortie details for each flight (see list below), the system provides a complete engine use history and data base that can be used to extrapolate to the entire aircraft population. The British decision to use a continuously recording simple system on a few test aircraft "was influenced by the fact that despite the large investment in FDR (Flight Digital Recorders) in the USA there was not a single program that had explored the full potential of EHM (Engine Health Monitoring) leading to the installation of a truly operational system applied fleetwide by a military operator."[14]

Table 29 illustrates typical aircraft sortie identification codes.

EXAMPLE OF SORTIE DETAILS

a. Aircraft Type and Mark: ....
b. Engine Type: ....
   Serial Number: ....
c. Aircraft Tail No.: ....
d. Date of Flight: ....
f. Duration of Flight: ....
g. Sortie Identification Code: ....
h. Cassette Serial No.: ....

Coupling the data obtained from the EUMS instrumented aircraft and the sortie codes, a frequency distribution for engine cycles per hour by sortie code is generated. The resulting statistics are extrapolated to estimate the remaining useful life of critical engine components for the entire aircraft population.

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[14] See Ref. 8.

Table 29

TYPICAL AIRCRAFT SORTIE CODES

Type of Sortie	Sortie Code
Initial Flying Training Exercises	L 21
Low-level Familiarization	L 22
Medium-altitude GH and Aeros	L 23
High-altitude GH and Aeros	L 24
Circuits	L 25
Low-level Navigation	L 26
High/Medium-level Navigation	L 27
High/Medium/Low-level Navigation	L 28
IF (Instrument Flying)	L 29
IF/GH/General Handling	L 30
Formation Flying	L 31
Night Flying	L 32

Data Acquisition. The airborne components of the EUMS consist of a digital Data Acquisition Unit (DAU) and a Quick Access Recorder (QAR). The DAU accepts the electrical outputs from a range of aircraft and engine transducers, samples these in a predetermined sequence, and converts each signal into a binary-coded 12-bit word. These data are then transmitted as a serial digital stream to the QAR. The serial digital data are recorded serially on a single track for a tape cassette in the QAR. The recording code, Harvard Bi-Phase, has the advantage of combining data and time on a single track. The QAR is a redesigned military voice recorder with a removable "Phillips-standard" tape cassette. The QAR provides a minimum continuous recording duration of two hours. The cassette is removed after each flight and mailed along with the sortie details to the central ground processing station, based at the Rolls-Royce plant in Bristol.

Ground Test Equipment. A portable test set has been developed for maintenance and calibration of the system. The unit provides all the necessary power and signals and can demultiplex a single parameter from the data stream and display it in both binary and decimal form. The primary use of the test set has been to fault-isolate to individual circuit boards and provide complete system calibration.

Data Processing. When the tape cassette is received at the central ground processing station, the data are reduced and an LCF count is derived for that sortie. The ground processing station consists of an airborne cassette replay unit, data recovery unit, and PDP8 and Texas Instruments 980 digital computers with associated peripherals. The system is entirely self-contained and suitable for use in a normal office environment. A long-range goal of the EUMS program is to develop the capability to play back the cassette during pilot debriefings to confirm or deny pilot-reported overtemperatures or reveal overtemperatures unmonitored by the pilot during the sortie. This is especially relevant in the case of the Harrier, where removal of the wing is required to remove the engine.

Data Analysis. At the central ground processing station, the LCF calculations use a Goodman diagram approach to assign to each stress cycle-rpm excursion a damage index relative to the stress level incurred by a full cycle. The total LCF damage incurred during the flight under analysis is the summation of the damage incurred and is expressed in number of equivalent full cycles. The cycles per sortie are then divided by flight time to yield cycles per hour. Flight times are obtained from the sortie detail form, which accompanies the cassette when forwarded by the squadron. The various sortie patterns are then collated and analyzed (see Fig. 9) and provide an assessment of overall aircraft cycle use for that sortie category.

Currently, as part of the evaluation process, the data are communicated to the National Gas Turbine Establishment at Pyestock, where efforts are directed at correlating experienced LCF with cycle damage as calculated from EUMS flight data. The EUMS has also provided Pyestock a clear picture of how the engine is being used and its

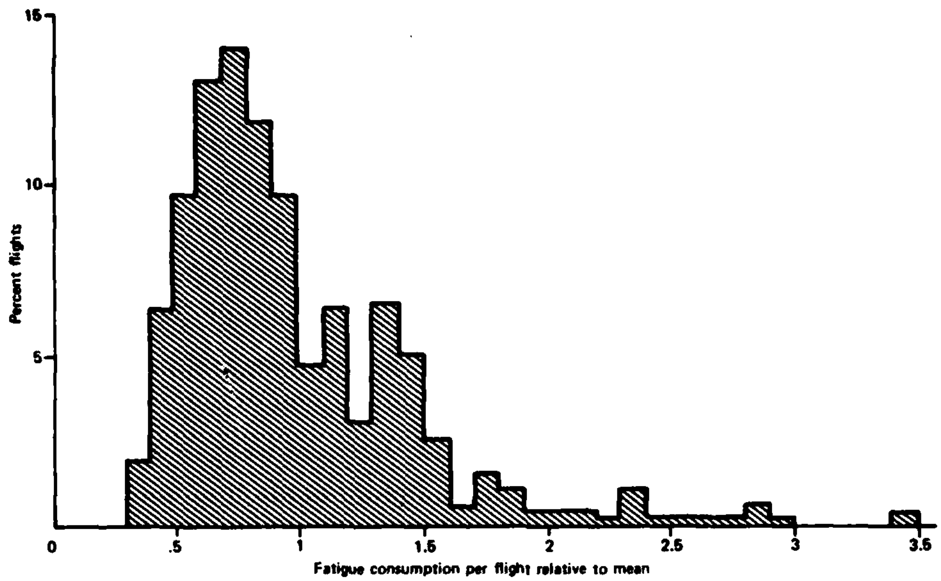

Fig. 9 — Typical distribution of fatigue consumption

operational duty cycles. These data are being used to construct realistic engine ground test cycles.

Experience

Analysis of the data has produced the LCF consumption for the relevant engines being monitored. A significant variation in LCF consumption has been found across aircraft, ranging from less than a cycle per hour to more than 40 cycles per hour depending upon the aircraft and sortie flown. In several cases, the average LCF consumption is lower than the original predictions, and steps have been taken to extend component lives in light of this latest knowledge. In this case considerable life improvements were realized along with cost savings.[15] Other engines have shown a higher LCF consumption rate and component lives have been adjusted to reflect this.

[15] In one instance where the original estimate of cyclic rates proved unduly pessimistic, components were retrieved from storage for reissue.

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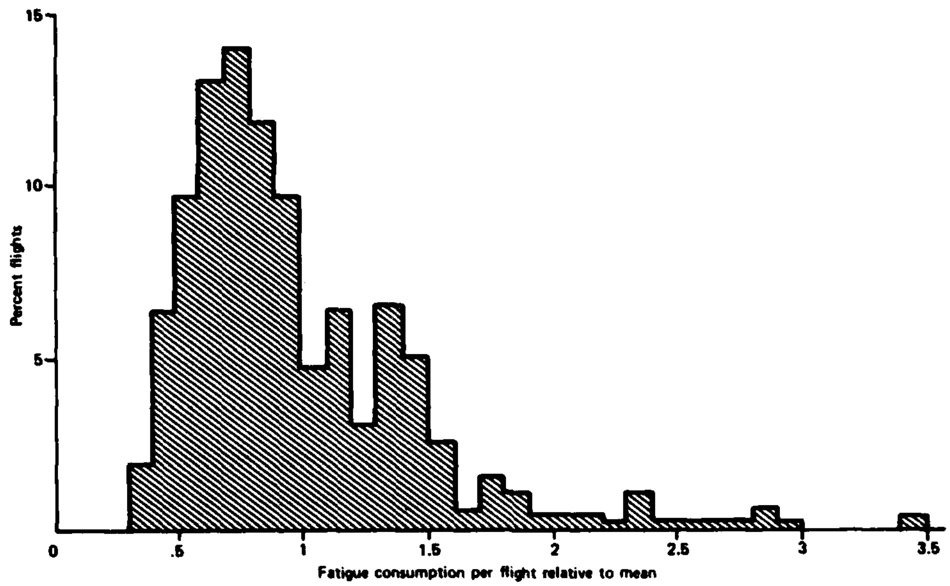

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[15] In one instance where the original estimate of cyclic rates proved unduly pessimistic, components were retrieved from storage for reissue.

Findings

An important difference between the U.S. and U.K. approaches is that EUMS was not originally intended to be a maintenance tool and currently has very little effect on base maintenance. However, staff concerned with base maintenance are beginning to use EUMS's potential. They are finding that they can confirm pilot complaints or provide historical operational data to yield insights into experienced engine malfunctions, particularly abnormalities. In the future EUMS should aid and improve the efficacy of base maintenance and could well become part of the U.K. support procedures and equipment scenario.[16]

As a result of the EUMS data, British engine managers expect to extract a greater percentage of critical engine components' useful life, with an improved safety margin. Current efforts are attempting to correlate engine malfunctions, material condition, and maintenance history with EUMS data.

Application of EUMS has yielded significant insight into the engine's operational duty cycle for British engine managers. The British have found, for example, that the amount of engine life consumed depends, to an important extent, on the type of missions flown and how the equipment is used during the mission. They also found that a major contributor to reduced engine life is the cumulative effect of small power transients. They have concluded--and the U.S. military services are also reaching the same conclusion--that engine failure modes, such as low-cycle fatigue, have not been as well understood as they were thought to be. Quantitative engineering data are now being used to improve engine design specifications and to bring both full-scale and component test cycles in line

[16] The British are expanding EUMS to an Engine Usage/Life Monitoring System (EULMS) concept. In addition to performing all the functions of EUMS, it will carry out those functions of other EHM systems and of some GTE (Ground Test Equipment) aimed at meeting specific engine airframe combinations' requirements in the areas of readiness and maintainability. Use is being made of recent hardware and software developments in the digital micro-electronics field. The accuracy/dependability of EUMS has recently shown that it is

with operational duty cycles. The British are in the process of reorienting their approach to maintainability and reliability, recognizing that these areas are more a function of engine throttle cycles experienced and the type of mission flown than of flying hours only.

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capable of giving sufficiently accurate engine performance data for their monitoring purposes. This is being exploited in EULMS where it is planned that a "quick read" readout/printout/tele display capability will be available.

IV. ANALYSIS OF THE DATA: ENGINE MONITORING SYSTEMS OUTCOMES

To evaluate the strengths and weaknesses of previous monitoring systems, we have devised the evaluation matrix shown in Fig. 10, based on the system expectations presented above in Table 2. System objectives are divided into two groups based on a time orientation: (1) near-term, maintenance-oriented operations, maintenance, and management effects; and (2) long-term, design-oriented benefits to management, testing, and future engine design. The taxonomy delineates the characteristics that we believe are desirable in a monitoring system. Certain of these characteristics were design objectives for each of the case studies. For example, as a result of engine monitoring, EHMS expected fewer maintenance manhours, a savings in fuel, fewer parts consumed, fewer unscheduled engine removals, and an extension in TBO.

The primary design objective of most monitoring systems was to reduce resources expended to maintain engines, so the five outcomes indicated by checkmarks in Fig. 10 received the most attention by those developing monitoring systems because, in principle, it is easier to estimate their costs. The first four checked characteristics have been important in providing justification for previous U.S. systems, but all characteristics must be considered in a new system because, in some cases, the unchecked characteristics may justify the costs of a new monitoring system.

To assess each monitoring system outcome, we use this matrix with the classification of Table 2 as row headings and the selected case studies as column headings. The color coding used requires some explanation. The red coding means the characteristic was not achieved, but it is important to point out that, in many cases, the characteristic was not a design objective and no attempt was made to achieve it. The yellow color coding signifies that the information necessary to determine if the monitoring system accomplished the objective is lacking. The green color coding indicates the characteristic was achieved or was beginning to be achieved. Several of the green

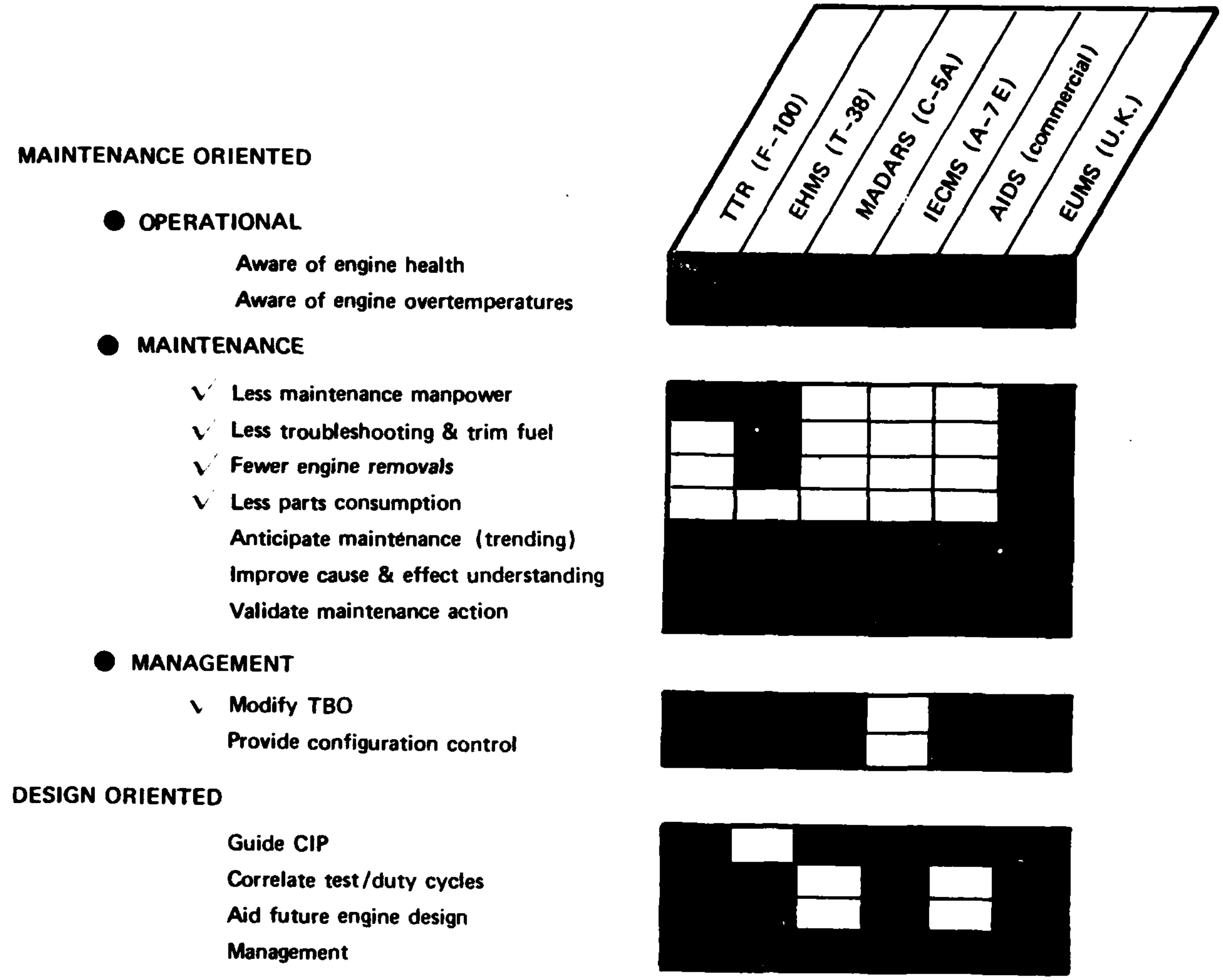

Fig. 10 — Summary of engine monitoring systems outcomes

blocks are crosshatched; this means benefits existed but additional explanation is required.

In the EHMS column, for example, both operational characteristics were achieved. Because overtemperature damages the most critical and most expensive engine components, this information is extremely important. Our research on engine overtemperatures of fighter and attack aircraft reveals that pilots report only about one-third of the significant engine overtemperatures and are unable to report their duration. This is to be expected, because these aircraft are mostly single-crew aircraft, and the pilot sits in a small, complex cockpit with many gauges. He must perform several other functions, whereas the monitoring system watches engine parameters full time. Often, it is only if the pilot "feels" that something is wrong that he will turn his attention to the gauges.

For the EHMS, the first three characteristics under maintenance are coded red because the instrumented engines consumed more maintenance manhours, troubleshooting, and trim fuel, and experienced a higher removal frequency, than the control group engines during the flight-test evaluation. The parts-consumption block is colored yellow because no data were collected.

The last three characteristics under maintenance are colored green because they were just beginning to be achieved, but achievement requires time to develop fully. Looking at the lower portion of the matrix, we see that the management and the long-term design-oriented blocks for the EHMS are red. Although the EHMS was not intended to achieve the long-term benefits, we believe the matrix is also telling us that when a diagnostic system is applied to a mature engine, it cannot have a substantial effect in these two areas (the TTR is a similar situation) because the engine is better understood, many problems have been corrected, and its service life is considered satisfactory for the time it will remain in the inventory.

In contrast, MADARS, IECMS, and AIDS were all installed either as original equipment or early in engine life. Each system records internal gas temperatures and pressures. Because all of them provide the operator with an awareness of engine health, these blocks are

coded green. Under maintenance, however, the first four characteristics are coded yellow because either all of these engines are instrumented (C-5A, AIDS) or there never has been an identified control group (IECMS).

The improved awareness and understanding provided by diagnostic systems have important effects on the latter three maintenance categories. For instance, in the case of fixed time maintenance procedures, the data can be used to analyze trends and change the problem into one that can be solved with a different maintenance schedule; the flight data improve the maintenance crew's cause-and-effect understanding, permitting them to be more knowledgeable about engine conditions. In several of the case studies--MADARS, IECMS, EHMS, and AIDS--these data are being used to avoid the shotgun approach to maintenance where good parts are needlessly replaced.

Unfortunately, these benefits take time to fully develop. Experiencing failures and reviewing the data leading up to the failures precede any attempt to correlate a particular trend with an incipient engine failure. Only when such correlation exists can the operations, maintenance, and management personnel use this information to schedule or initiate maintenance.

The crosshatched green, in the case of modifying the TBO for the MADARS, indicates that the monitoring system data provide one of many inputs that constitute the information set enabling extension of TBO. The technical data provided by the monitoring system help establish the proper TBO in three ways: first, by providing additional confidence to the decisionmaking process; second, by identifying failure modes that are at present undetected in fleet engines; third, by verifying the reliability and durability of new parts and components incorporated into the engine.

For the IECMS, the green crosshatching shows that the long-term benefits were not part of the original monitoring objectives but resulted from an engineering need to better understand engine operation. The IECMS developed a continuous recording option, which enhances this understanding. These data permitted the operational duty cycle to be correlated with appropriate testing. This is an

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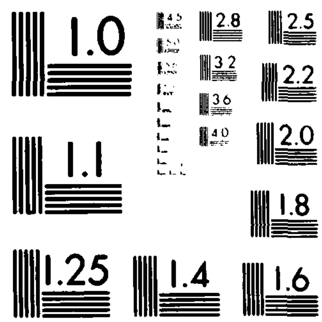
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extremely important contribution, because without correlation, operational fleet failure modes may not be reproduced in the test cell. These data are proving useful to future engine design efforts. Examination of the matrix reveals that the U.S. monitoring systems have emphasized the short-term, maintenance-oriented benefits. In contrast, the British Engine Usage Monitoring System has initially *ignored the maintenance-oriented* benefits, choosing instead the longer-term design, testing, and management benefits.[1] The U.S. Air Force and Navy have also recognized the need to gather quantitative engineering data on engine operational duty cycles. This duty cycle research is discussed in the next section.

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[1] This situation is changing. The U.K. system is moving toward day-to-day operations.

V. ENGINE DUTY CYCLE RESEARCH

BACKGROUND

Military aircraft systems are designed for and evaluated against Request For Proposal (RFP) missions based on projected mission/combat times with specific weapons load and avionics suite. RFP missions focus on range, combat and loiter time, single-engine hot-day capability, etc. Until recently, there was very little provision for defining actual fleet operations--training, testing, etc.

The history of gas turbine development has been in the direction of increased performance and reduced weight. Rushing to realize this tactical advantage in system performance has in almost every case resulted, initially, in low reliability and durability levels. As latent design deficiencies surface, post-qualification or component improvement programs enlarge to consume a considerable amount of resources while addressing these problems. To overcome the spate of historical problems occurring within the first few years of engine deployment, the Air Force and Navy, like the British, are now attempting to improve their understanding of how engines are used in the operational environment. This orientation results from suspicions, now confirmed, that operational use may be more severe than indicated by the synthetic RFP profiles serving as design guidance to the manufacturers and that testing has not matched the duty cycle experienced in actual service.

DUTY CYCLE TESTING

The Air Force and Navy are moving toward a new concept in testing that more closely duplicates operational stresses to overcome problems associated with the durability of a new engine. The Air Force ground test program is called Accelerated Mission Test (AMT). It is based on engine cycling to more closely duplicate throttle movement in all missions. The AMT is being applied to the F100 engine program. It is built around data from an Events History Recorder (EHR) mounted on each F100 engine. The EHR tracks time at

rated turbine temperature and counts full-throttle transients from idle to military power and above. The Air Force has lead-the-fleet (LTF) aircraft accumulating early mission experience for feedback to designers and operators.

. In contrast to the Air Force approach, Navy engineers visit fleet squadrons and obtain actual training and operational mission profiles from both Navy and Marine pilots. Wing records provide the mission mix. With the mission profiles defined, aircraft are instrumented and flown to that profile. Data are recorded, usually at one-second intervals, on a few parameters of interest. Then engines are tested on the ground through Simulated Mission Endurance Tests (SMET).

EXPERIENCE

A major benefit of this improved understanding and quantification of an engine's operational duty cycle is that test cycles and future engine design specifications can be correlated with operational use to improve engine durability for specific missions of interest. Realistic test cycles help determine service suitability of new engines and their components. As an example of how these data are being used, the Navy's F-18 powerplant, the General Electric F404, was examined in terms of expected usage based on data from A-7, F-4, and F-14 experience. The results showed that more cycling than originally expected would have caused greater wear and increased travel on all variable geometry actuators and linkage, especially the exhaust nozzle. This improved understanding permitted these components to be redesigned early in the development program, thus obviating the need for an expensive retrofit program. Other areas of the engine required redesign in order to maintain specified durability.

The USAF discovered that several engine problems (which caused recent flight restrictions with the F-15) were related to engine design specifications that were not compatible with the stresses encountered during a high number of throttle movements in normal

fighter operations.[1] AMT data are providing direction to the F100 component improvement program, in that AMT engines have successfully detected fatigue and erosion problems ahead of fleet engines in time to set limits and substantiate redesigns.[2] The AMT engines are also used to substantiate needed engineering changes before such changes are approved.

The Navy data show significant increases in frequency of throttle excursions compared with those originally estimated. For example, the type of early information supplied to the engine manufacturer for design guidance for a new engine is shown in Fig. 11 for the Navy F-14.[3] The RFP estimated power required as a function of time for the F-14 intercept mission is shown in view (a). The actual engine cycles that occurred on an instrumented F-14 during flight is shown in view (b). The resulting change in the predicted design life of certain important engine components is shown in the table in Fig. 11b.[4] Low-cvcle fatigue is important because cumulative fatigue damage occurs in cyclically loaded parts as these parts are cycled from low to maximum RPM. Current methods for calculating LCF rely on the usage[5] rates of cycles per hour that are derived from synthetic sortie patterns.[6]

The <u>continuously recorded flight test data</u> show a different picture for the frequency of both major and minor cycles. Because this increase in the frequency of major and minor cycles is significant

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[1] References 7, 8, 23, 24, and 25 discuss this in greater detail.

[2] Reference 21 discusses F100 efforts and experience to date.

[3] Propulsion systems are designed to Request for Proposal (RFP) mission profiles based on a projected combat time with specific weapons load and avionics suite.

[4] Engine duty cycle effect on part life and maintenance intervals is discussed in Refs. 22, 23, 25, and 27.

[5] Fatigue fracture is the most unexpected service failure. Corrosion and wear probably are more frequent, but they are gradual and expected.

[6] The sortie pattern is not the only variable. One example of recent IECMS data shows a significant difference in engine use by a flight leader and wing man during the same mission.

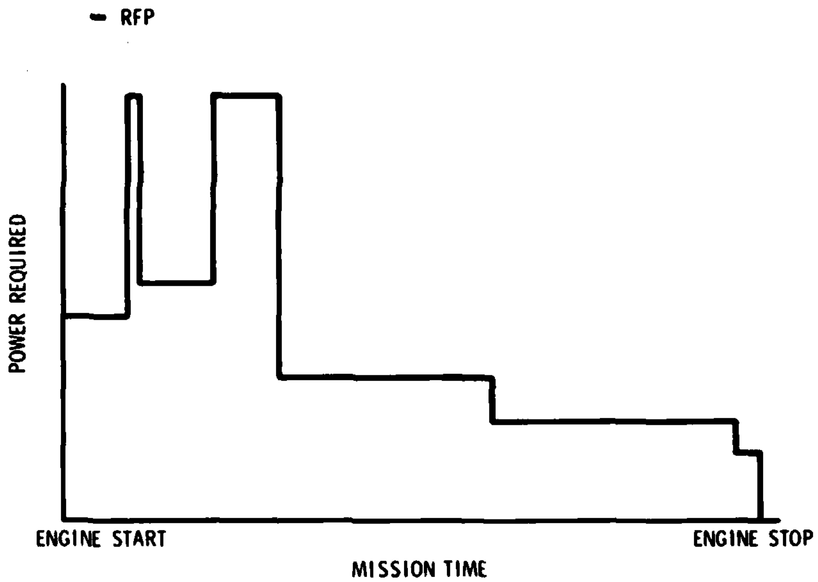

Fig. 11a — F-14 power required profile

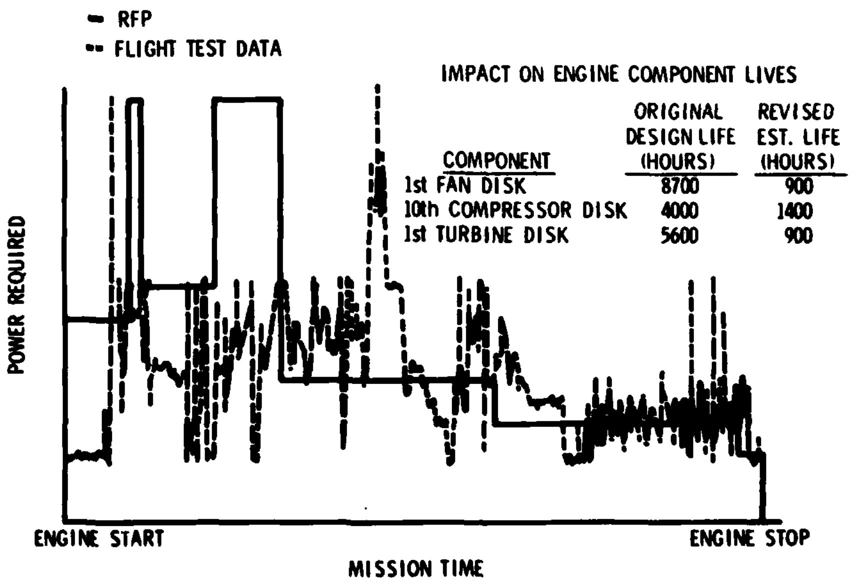

Fig. 11b — F-14 power required profile

and was not originally anticipated, it is contributing to current engine problems. The data demonstrate the gross errors in synthetic sortie analysis and, surprisingly, show that neither the service nor the manufacturer has had a clear idea of engine operational use. As a result, engine part life has been overestimated; hence, life-cycle costs have been underestimated. Analysis of continuously recorded data has resulted in the original estimate of engine part life in some cases being reduced by an order of magnitude. This type of information needed by the designer is available only through continuous recording. If, for example, continuously recorded data had been available from previous fighter aircraft mission experience, the F-14 powerplant, an uprated model of the TF30, might have been redesigned differently.

VI. FINDINGS AND CONCLUSIONS OF THE CASE STUDIES AND DUTY CYCLE EXPERIENCE

Before drawing any conclusions regarding implications for future monitoring system programs, we need to summarize the findings of our case study reviews and the engine operational duty cycle work. These findings are as follows:

Outcomes from previous engine monitoring applications are not conclusive. The benefits and costs of engine monitoring are still very uncertain. Hoped-for benefits have not been realized, and costs have been higher than expected. Confusion exists as to the costs and benefits that such an engine diagnostic system might reasonably provide. None of the potentially important system and engine benefits--improved readiness, availability, reliability, and lower intermediate and depot maintenance costs--were demonstrated, in part because the controls necessary to the collection of data appropriate for analysis were not maintained over a sufficiently long test period. Current objectives of monitoring systems are oriented to cost reduction, and the lack of control for certain potentially important variables results from a lack of emphasis on noncost-oriented benefits, which can be extremely important. In spite of additional unscheduled engine removals, maintenance manhours, and fuel used, no measurable positive output--no cost savings and no increase in readiness or availability--was discernible from the EHMS or TTR experience. Perhaps the engine's maturity and the shortness of the test explain the lack of positive outputs.

Continuous recording provides important design information. A continuous recording system provides important design information that can be of substantial value to the Air Force, although many of the important benefits cannot now be treated quantitatively. Time is required to assimilate this information and to develop and fully utilize the data derived from the monitoring procedure. Specific action will be necessary if we are to obtain certain long-term benefits. The maximum utility of the monitoring process occurs early in

an engine's life when it is still possible to affect engine component redesign and to give direction to the component improvement program.

Monitoring systems have been designed to deal with the problems of those supporting their development. Most of the U.S. selected case studies had a maintenance orientation that reflected the sponsoring organization's interests. In contrast, the British system initially ignored the maintenance orientation in favor of achieving engineering benefits--again in line with the sponsoring organization's mission.

Modifications after some operational use are almost always desirable. The detailed design of a monitoring system must depend to some extent on engine characteristics that are revealed only after experience. Therefore, improvements in the monitoring system design should evolve as we gain experience with the system.

Monitoring systems do provide improved awareness of engine health. Monitoring systems provide the engine design and test community and maintenance crew with an understanding of problem causes and effects and, through corrective actions, ultimately improve the material condition of the engine. Engine overtemperatures are especially important, particularly in the case of a single-pilot and a single-engine aircraft.

Monitoring tends to increase early support costs. The increased sensitivity of pilots and ground crews to engine condition does result in more malfunction reports and consequently increases costs initially. Problems are identified and resources must be allocated to correct them. Another source of increased costs is the low reliability and high false-alarm rates experienced by most of the monitoring systems during initial operations. Together, these two factors can initially result in a low system credibility, a handicap difficult to overcome.

Monitoring a sample of a particular engine model yields benefits. In several of the case studies, only a small sample of a particular engine model was monitored. Nevertheless, much was learned about the engine and its operation while operational experience was being obtained with the monitoring system.

Several monitoring system development programs were dominated by hardware and software problems. Several of the programs have been dominated by early monitoring-system hardware and software problems such as latent design deficiencies, manufacturing defects, nonavailability of key software subroutines, and logic errors in software. These problems continue even after monitoring systems reach the field. It takes a long time to work out all the bugs, and this drives up initial support costs, especially when systems are prematurely fielded. These early problems are difficult to overcome, but, again, for both short-term maintenance and longer-term design and testing, the benefits appear significant if these problems can be resolved.

There has never been a controlled experiment with a maturing engine over a long enough time period to allow monitoring system outcomes to be quantified. However, some conclusions can be drawn based on our case studies:

(1) The maintenance cost savings used to justify a new monitoring system are unlikely to materialize over the short term. But whether monitoring systems pass or fail in the narrow sense of cost savings over the short term should not be the sole criterion on which they are judged. Substantial value lies in the potential benefits of (a) anticipating needed maintenance, (b) helping maintenance crews and engineering support personnel to better understand cause and effect of engine failure, and (c) verifying that maintenance has been properly performed. These benefits are especially significant now that the Air Force is moving to an on-condition maintenance posture, as is envisioned for future military turbine engines. They can also be important in helping to achieve the original design objectives of the monitoring systems. Unfortunately, none of these benefits can be quantified on the basis of experience to date.

(2) Historically, tests of engine monitoring have not yielded conclusive evidence on the value of engine monitoring, because the test aircraft sample was too small and programmed flight hours were too few. In several important areas, the program focus was too narrow. For example, the software and data processing were not given

enough support within the overall system, and the long-term design-oriented benefits were not given proper consideration. With the exception of IECMS, U.S. monitoring programs have omitted valuable long-term returns, such as long-term design feedback and improvement in test cycles. This type of information should help the Air Force in its component improvement program, as well as in future engine design programs. It is especially important to have a balanced program now that reliability, durability, and cost issues are almost on an equal footing with performance.

A direct comparison between military and commercial objectives is not possible, because the system outputs are not measured the same way. Military concerns reflect capability or military worth within the context of national security, while the commercial operators emphasize safety of flight and an adequate return on investment.[1] The military needs are of much broader scope. The USAF has the prerogative to invest in technologies that are not cost effective in the short term but are felt to have military worth in the future.

Thus, although the overall short-term military and commercial objectives are somewhat similar, in the long term the military must be concerned with and take steps to improve future capability--a task requiring investment in technologies where the payoffs are generally rather than specifically conceived.

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[1] In today's economic environment, commercial airlines require a one-year (100 percent) return on investment (ROI) for minor mods, a 3-5 year ROI for major mods such as re-engining, and a new aircraft must pay for itself within seven or eight years.

VII. RECOMMENDATIONS

The Air Force should establish a single office whose task is to test turbine engine monitoring system concepts with the goal of developing such a system both for engines recently introduced into service and for future engines. Because the development problems of the monitoring system tend to obscure and confuse the benefits to be derived, designs should eventually converge to a few generic configurations with many common elements.

To date, monitoring systems have naturally emphasized the problems of those supporting their development--maintenance, operational, or design communities. A more balanced approach should be initiated. All communities need to be involved (through a single office) during the design, testing, evaluation, and operational life of the system.

The scope of U.S. military turbine engine monitoring systems should be broadened to include the valuable contribution that information feedback can make to the designer over the long term. Of particular importance is a correlation between testing and operational duty cycles. Mission profiles can change because of differing operational scenarios and threats.[1] For example, the F-15 and F-16 use models of the same engine, but the mission profiles are quite different and the engines for each application should be tested to the relevant duty cycle. These benefits require a <u>continuous recording</u> option and a small staff dedicated to analyzing the data obtained and getting such data back to designers. As currently designed, most monitoring systems have sensed, but have not saved, the data necessary for improving future engine design. A small device, perhaps a plug-in module, to save the data would be sufficient to provide the necessary design information. This device needs to be installed on only a handful of aircraft at each operational location. Constant

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[1] If aircraft use is changed, the operational duty cycle for the engine must be redefined, because a change in usage will cause different failure modes in the engine.

updating of usage data is required to maintain currency with fleet operations.

Because there is a great deal of uncertainty about the costs and benefits of engine monitoring, a *flexible implementation* schedule that has a comprehensive test program must precede a full-scale production go-ahead for a monitoring system. Not only will the phased implementation maintain program flexibility, but it will permit establishment of an engine group to control for all the variables needed for a complete understanding of the cost and benefits of monitoring. Monitoring system hardware and software problems can then be experienced in a small sample of aircraft rather than accrued over an entire aircraft inventory. The additional time gained with an incremental implementation schedule can be used to determine if the desired objectives can be satisfied by instrumenting a small sample of the aircraft inventory. The option of not instrumenting the entire fleet should be included as a possibility in the decision-making process. Because the benefits of monitoring ultimately depend on good cause and effect correlations, this recommendation would more rapidly build a data base of operational and maintenance cause and effect history.

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